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ULTRAHIGH VACUUM, HIGH TEMPERATURE, LOW CYCLE FATIGUE OF COATED AND UNCOATED RENE' 80

FINAL REPORT

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TRW MATERIALS TECHNOLOGY LABORATORIES

CLEVELAND, OHIO

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16. Abstract

A study was conducted on the ultrahigh vacuum strain controlled low cycle fatigue behavior of uncoated and CODEP B-1 aluminide coated Rene' 80 nickel-base superalloy at 1000°C (1832°F) and 871°C (1600°F). The results indicated little effect of coating or temperature on the fatigue properties. There was, however, a significant effect on fatigue life when creep was introduced into the strain cycles. The effect of this creep component was analyzed in terms of the method of Strainrange Partitioning. The longest lives were obtained with $\Delta\varepsilon_{pp}$ type cycling, while the $\Delta\varepsilon_{cc}$ cycle caused a reduction of fatigue life of about 1/2 order of magnitude with respect to the $\Delta\varepsilon_{pp}$ life. The $\Delta\varepsilon_{cp}$ type cycle caused a life reduction of slightly less than 1 order of magnitude with respect to the $\Delta\varepsilon_{pp}$ life, while the $\Delta\varepsilon_{pc}$ type cycle provided a fatigue life approximately 1 order of magnitude below that of the $\Delta\varepsilon_{pp}$ life.

Metallographic evaluation indicated that microstructural damage varied with cycle type and test temperature. Specimens tested with the $\Delta\varepsilon_{pp}$ type deformation exhibited a transgranular fracture mode. Specimens with the $\Delta\varepsilon_{pc}$ type deformation exhibited an intergranular fracture mode with extensive grain boundary sliding resulting in steps or grain extrusions particularly at 1000°C (1832°F). Specimens tested with the $\Delta\varepsilon_{cp}$ type deformation exhibited an intergranular fracture mode while the $\Delta\varepsilon_{cc}$ specimens exhibited different fracture modes depending on test temperature. At 1000°C (1832°F) the fracture mode was intergranular while at 871°C (1600°F) the fracture mode was transgranular.

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FOREWORD

The work described in this report was performed in the Materials Technology Laboratory of TRW Inc. under the financial sponsorship of the U.S. Army Air Mobility R&D Laboratory for the National Aeronautics and Space Administration, Contract NAS-3-17830. The program was administered for TRW By Dr. H. E. Collins, Program Manager. The Principal Investigator was Dr. C. S. Kortovich, with technical assistance provided by Mr. J. W. Sweeney. The NASA Technical Manager was Dr. G. R. Halford.

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I INTRODUCTION

The use of diffusion aluminide protective coating systems on superalloys in gas turbine engines for the improvement of oxidation and hot corrosion resistance has become quite widespread as a result of increasing cycle temperatures. Although they accomplish this purpose, there is concern that such coatings may degrade the mechanical properties of coated hardware. Of particular concern is a reduction of fatigue resistance in complex geometry hot section components such as turbine blades and vanes which experience severe thermal-mechanical strain cycling during engine service.

The application of a coating to the surface of a material can have a number of effects relevant to the fatigue properties of the coating-substrate system (1). For example, the deformation behavior of the substrate may be changed by the presence of a surface layer having a different elastic modulus and yield strength from that of the substrate. If the fatigue properties of the coating are better than that of the substrate, increased life may be expected. On the other hand, if the fatigue properties are poorer than the substrate, cracks in the coating will serve as surface notches and as paths for the degrading environment to reach the substrate, resulting in reduced fatigue life. In general, the effect that a coating has on the fatigue properties depends on the strainrange, the maximum tensile and compressive strain, temperature, frequency and the nature of the coating itself (1).

The present study was undertaken to provide further insight into the thermal-mechanical fatigue behavior of the nickel-base superalloy Rene' 80 in the coated (CODEP B-1) and uncoated condition. This program involved closed-loop, servo-controlled fatigue testing with independently programmed temperature control and strain cycling to develop baseline data for analysis of thermal fatigue behavior by the method of strainrange partitioning (2). Tests were performed in air and in vacuum to separate the effects of environmental interactions from mechanical effects of the coating on fatigue behavior. Interpretation was made of the influence of thermal cycling on fatigue life within the framework of the strainrange partitioning concept by correlating microstructural damage with various types of reversed inelastic strain cycles involving reversed and unreversed tensile and compressive creep deformation. The program was a cooperative effort between the Materials Technology Laboratory of TRW Inc. and the Materials and Structures Division of the NASA-Lewis Research Center, with vacuum tests being performed at TRW and air testing at NASA. This report presents the results of the vacuum fatigue tests performed at TRW.

II EXPERIMENTAL PROCEDURES

For this program the effect of CODEP B-1 aluminide coating on the thermal-mechanical fatigue behavior of nickel-base superalloy Rene' 80 was evaluated. The program was divided into three tasks, specimen preparation, cyclic fatigue tests and supplementary mechanical property testing. In the following sections the experimental procedures for each task are discussed.

A. Task I - Specimen Preparation

The specimens used for the present study were the individually cast, tubular, hour glass-shaped specimens with threaded ends as per NASA Drawing CB-300740, shown in Figure 1. The specimens were originally cast as solid bars and were then machined to the proper configuration. The composition of the material used for this program is listed in Table I. Uncoated specimens were given the following heat treatment:

1218°C (2225°F)/2 hours vacuum/argon quench to room temperature

1093°C (2000°F)/4 hours vacuum/argon quench to room temperature

1052°C (1925°F)/4 hours vacuum, furnace cool in vacuum to 649°C (1200°F) within 1 hour, air cool to room temperature*

843°C (1550°F)/16 hours vacuum/furnace cool to room temperature

Coated specimens were prepared with the CODEP B-1 aluminide coating. The alumina precoat was deposited on both the internal and external surfaces of the specimens by the electrophoresis technique. All other aspects of the coating application process conformed to General Electric Company Specification No. F50T58-S1. The resulting coating thickness was approximately 0.05mm (0.002 inch). The coated specimens were given the following heat treatment cycle:

1218°C (2225°F)/2 hours vacuum/argon quench to room temperature

1093°C (2000°F)/4 hours vacuum/argon quench to room temperature
coating cycle as per Specification No. F50T58-S1

843°C (1550°F)/16 hours vacuum/furnace cool to room temperature

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* This simulates coating cycle

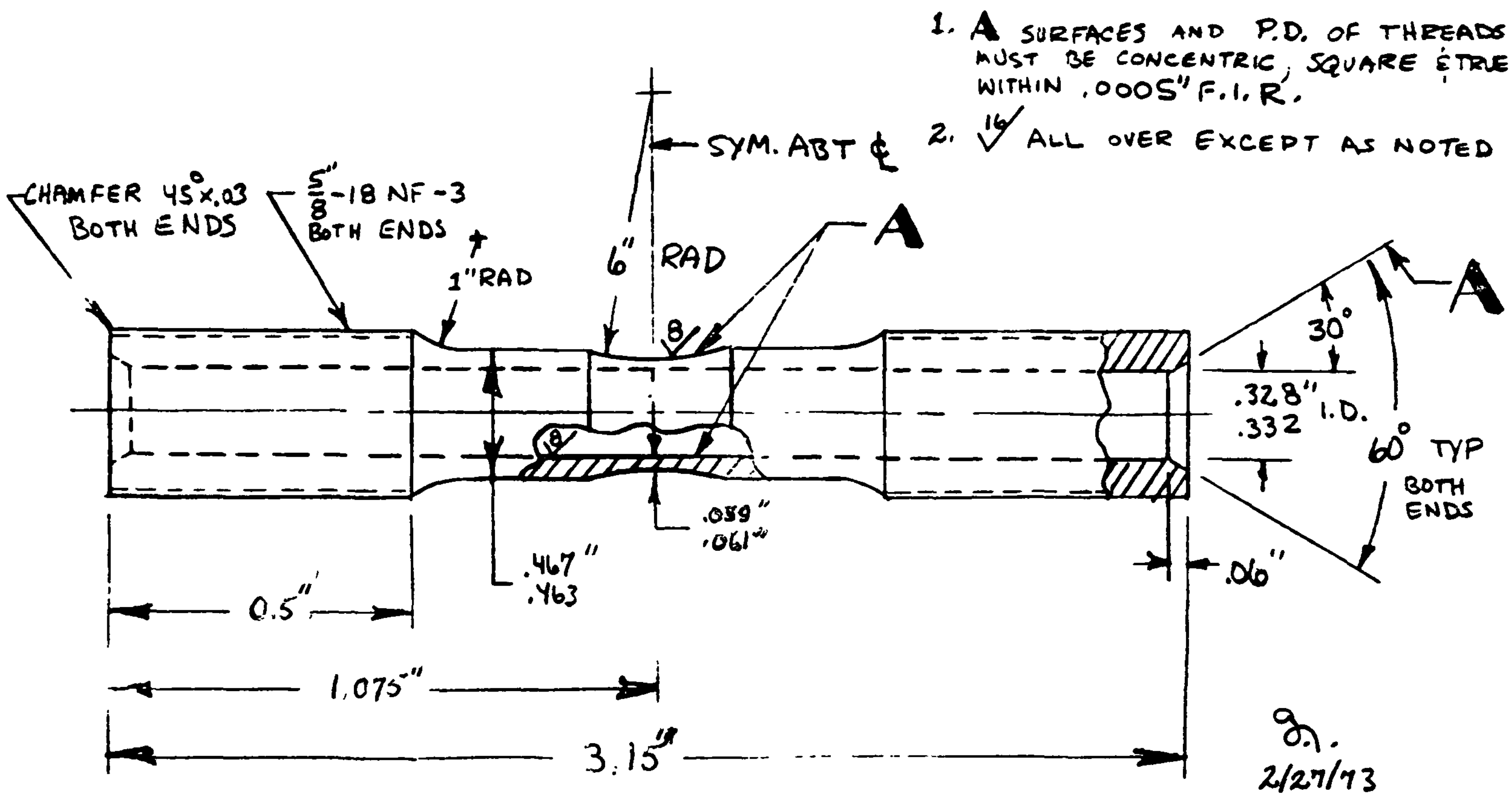


Figure 1. Fatigue test specimen

TABLE I

COMPOSITION OF RENE' 80 MATERIAL UTILIZED FOR LOW CYCLE FATIGUE TEST PROGRAM (w/o)

Element	Composition (1)	Nominal Composition (2)
C	0.17	0.17
Si	<0.05	-
Mn	<0.02	-
Cr	13.80	14.0
Mo	4.11	4.0
Fe	0.13	-
Ti	4.87	5.0
Al	2.99	3.0
Co	9.73	9.5
W	3.94	4.0
Zr	0.043	0.03
B	0.015	0.015
Ni	Balance	Balance

(1) TRW Master Heat BL 5138

(2) ASTM Data Series Publication No DS9E

B. Task II - Cyclic Fatigue Tests

The basic fatigue test program involved isothermal strain cycling to measure the four basic types of creep-fatigue life relationships defined by the strainrange partitioning method (2). The basis of this approach is the concept that two modes of inelastic deformation must be considered during low cycle fatigue, plastic flow and creep. These may exist separately or concurrently, and their interaction can influence the fracture behavior of a material to a considerable degree. Plastic flow is regarded as the sum of all inelastic strain components which occur nearly immediately upon application of stress (time independent) while creep is regarded as the sum of all time-dependent components. A major factor in strainrange partitioning is the shape of the stress-strain hysteresis loop during completely reversed straining and the manner in which the tensile and compressive components of strain are applied.

Strainrange partitioning is based on separation of the reversed inelastic strainrange into components which represent both the direction and the nature of the deformation. The critical point involves how the deformation is reversed in the fatigue cycle. Four basic types of reversed strain are defined:

$\Delta\varepsilon_{pp}$, tensile plastic strain reversed by compressive plastic strain

$\Delta\varepsilon_{cp}$, tensile creep strain reversed by compressive plastic strain

$\Delta\varepsilon_{pc}$, tensile plastic strain reversed by compressive creep strain

$\Delta\varepsilon_{cc}$, tensile creep strain reversed by compressive creep strain

The idealized hysteresis loops for these are shown in Figure 2.

pp strain is experienced at low temperatures, where creep does not occur, or at a high temperature and frequency where thermally activated flow is prohibited. cc deformation occurs in a low frequency, high temperature cycle where the strain rate is low enough that essentially all of the inelastic strain occurs by creep. Pure cp and pc types of deformation would be found in cycles where all of the deformation in one direction occurs at a low temperature and all of the reverse deformation takes place at a high enough temperature and low enough strain rate so that all of the reversed strain occurs by a thermally activated flow mechanism. Another case where this type of deformation might occur would be an isothermal cycle where the tensile and compressive strain rates are not equal so that one half of the cycle sustains more creep deformation than the other half.

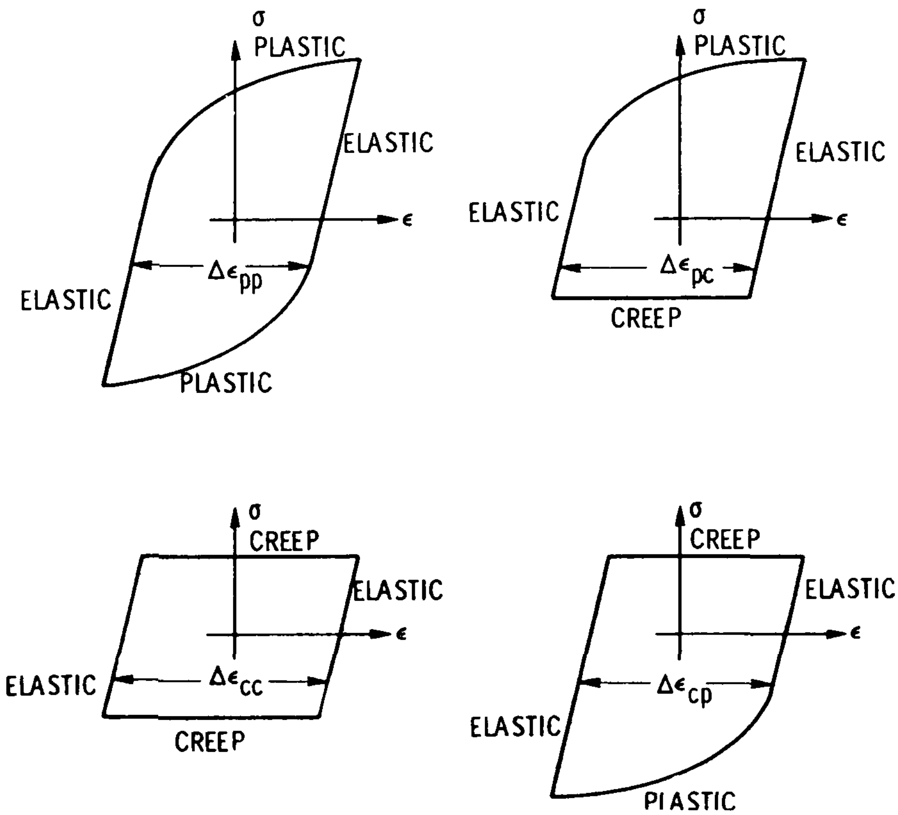


Figure 2. Idealized hysteresis loops for the four basic types of inelastic strainrange.

The basic test program for the present study was conducted at 1000°C (1832°F) and in an ultrahigh vacuum environment below 10^{-7} torr. On the basis of the results obtained from this basic program, similar tests were conducted at 871°C (1600°F) in a poorer vacuum (approximately 10^{-6} torr) to determine the effect of the variation of these parameters on the four basic types of creep-fatigue life relationships defined by the strainrange partitioning method. In order to more completely define the effect of the temperature variable on low cycle fatigue life a series of pp type tests were conducted on uncoated material at a range of temperatures from the ambient to 1000°C (1832°F) in the poorer vacuum.

Equipment and procedures used for the vacuum thermal fatigue tests on this program have been described in detail in previous reports (3,4). Briefly, the test apparatus was designed to perform completely reversed push-pull fatigue tests on hour-glass specimens using independently programmable temperature and strain control. Temperature was programmed using a thyratron-controlled 50 KV AC transformer for direct resistance heating of the specimen, while diametral strain was controlled directly using an LVDT type extensometer coupled to a programmable closed loop electrohydraulic servosystem. The measured specimen diameter was compensated electronically for thermal expansion so that net mechanical strain was controlled directly. Load, diameter and temperature were recorded continuously, with load-diameter hysteresis loops being obtained at periodic intervals during each test. Tests were conducted over a range of strain amplitudes (as measured by the width of the hysteresis loop at zero load) versus cycles to failure. Fatigue failure was defined in all cases as complete separation of the specimens into two pieces. Fractured specimens were sectioned longitudinally and examined metallographically to evaluate the character of the microstructural damage associated with each of the applied cycles.

C. Task III - Supplementary Mechanical Property Tests

Supplementary vacuum tensile and creep-rupture tests were also conducted in this program to provide baseline characterization data. All supplementary tests were conducted in ultrahigh vacuum (below 10^{-7}) at 871°C (1600°F) and 1000°C (1832°F) using tubular hour-glass specimens identical to those used for fatigue tests. Tension tests were conducted on both coated and uncoated specimens using a crosshead extension rate approximately equal to the frequency of the pp type fatigue tests (1.0 Hz). Properties measured were 0.2% offset yield strength, ultimate tensile strength and % reduction of area. Creep-rupture tests were conducted at constant load on coated and uncoated specimens. Reduction of area and rupture life were measured in these tests and a recording against time of the axial creep strain up to failure was also obtained.

III RESULTS AND DISCUSSION

A. Fatigue Test Results

The dynamic stress-strain response (hysterisis loops) for all the fatigue tests conducted in this program are presented in Appendix A along with a list of the elastic modulus at each test temperature used to calculate the elastic strain. In the following discussion PP, PC, CP and CC will refer to $\Delta\varepsilon_{pp}$, $\Delta\varepsilon_{pc}$, $\Delta\varepsilon_{cp}$ and $\Delta\varepsilon_{cc}$ types of deformation, respectively. All PP tests were conducted at approximately 1 Hz. For the PC and CP tests the time required to reverse the creep portion of the cycle by plastic strain and then initiate the creep portion again was 1 second or less. For the CC tests the time required to initiate creep in the reversed direction was also 1 second or less.

The fatigue life results are summarized in Tables II - VI. Table II lists the results of tests conducted at 1000°C (1832°F) and 871°C (1600°F) for uncoated and coated material tested with the PP type cyclic deformation while Tables III, IV and V list results for tests conducted with the PC, CP and CC types of deformation, respectively. Note that in Table III, containing the PC results, eight tests were conducted on uncoated material at 1000°C (1832°F) instead of the usual five. Three extra tests (89U-PC-1, 94U-PC-14 and 97U-PC-15) were conducted here because analysis of the data for the first five tests indicated that drift may have occurred in the zero point for the load and strain control settings resulting in erroneous readings. Thus, the values of total, inelastic and partitioned inelastic strainrange may be in error. Table VI lists the results of tests conducted at a number of different temperatures on uncoated material with the PP type deformation in a poorer vacuum (approximately 10^{-6} torr).

The ultrahigh vacuum fatigue life results from Tables II - V are plotted against longitudinal strainrange in Figures 3-6. For the remainder of the discussion, the term strainrange will always refer to longitudinal strainrange. Each figure contains three different graphs including a plot and a least squares fit of total strainrange versus observed cycles to failure, inelastic strainrange versus observed cycles to failure and partitioned inelastic strainrange versus life relationships computed using the interaction damage rule (5). Figures 3 and 4 contain results for tests conducted at 1000°C (1832°F) for uncoated and coated material, respectively, while Figures 5 and 6 contain results for tests conducted at 871°C (1600°F) for uncoated and coated material, respectively.

TABLE II

SUMMARY OF RENE' 80 FATIGUE TEST RESULTS FOR THE $\Delta\varepsilon_{pp}$ TYPE DEFORMATION

Specimen Number	Test Temperature °F	Test Temperature °C	Half-Life Axial Strain Range (MM/MM) Total	Elastic	Inelastic	Partitioned Inelastic	Half-Life Axial Stress Range Maximum (ksi)	Maximum (MN/M²)	Minimum (ksi)	Minimum (MN/M²)	Total Elapsed Time to Failure (Hours)	Actual Cycles to Failure
						Uncoated Specimens						
4U-PP-3	1832	1000	.00944	.00378	.00566	$F_{pp} = 1$	40.5	279.3	38.4	264.8	.1	306
5U-PP-4	"	"	.00277	.00122	.00155	"	13.4	92.4	12.2	84.1	1.7	6,302
6U-PP-5	"	"	.01250	.00363	.00887	"	40.4	278.6	35.4	243.4	.02	103
7U-PP-6	"	"	.00561	.00265	.00296	"	27.7	191.0	27.7	191.0	.6	2,298
8U-PP-7	"	"	.00247	.00169	.00078	"	17.0	117.2	18.4	124.8	5.9	22,115
21U-PP-8	1600	871	.00851	.00529	.00322	$F_{pp} = 1$	60.5	417.2	60.0	413.7	.2	642
22U-PP-9	"	"	.00241	.00215	.00026	"	26.2	180.7	22.8	156.5	44.0	163,533
41U-PP-10	"	"	.00630	.00451	.00179	"	50.9	350.9	51.8	357.1	.4	1,410
42U-PP-11	"	"	.00296	.00245	.00051	"	23.5	162.1	32.2	222.0	58.5	217,620
74U-PP-13	"	"	.01262	.00657	.00605	"	75.6	521.2	74.0	510.2	.04	145
						Coated Specimens						
43C-PP-1	1832	1000	.00152	.00101	.00051	$F_{pp} = 1$	10.4	71.7	10.8	74.4	55.5	206,460
45C-PP-3	"	"	.00490	.00247	.00243	"	25.9	178.6	25.7	177.2	.6	2,188
47C-PP-4	"	"	.00343	.00177	.00166	"	18.7	128.9	18.3	126.2	2.5	9,412
49C-PP-5	"	"	.00225	.00159	.00066	"	16.9	116.5	16.4	113.1	27.2	101,184
75C-PP-10	"	"	.00961	.00388	.00573	"	41.4	285.5	39.7	273.7	.1	233
51C-PP-6	1600	871	.00672	.00452	.00220	$F_{pp} = 1$	51.5	355.1	51.5	355.1	.5	1,860
52C-PP-7	"	"	.00742	.00512	.00230	"	59.4	409.6	57.2	58.6	.4	1,365
54C-PP-8	"	"	.00410	.00324	.00086	"	33.5	231.0	40.2	277.2	19.4	71,982
55C-PP-9	"	"	.00191	.00145	.00046	"	16.6	112.4	16.4	113.1	114.8	426,870
77C-PP-11	"	"	.01011	.00569	.00442	"	65.6	452.3	64.0	441.3	.1	293

TABLE III

SUMMARY OF RENE' 80 FATIGUE TEST RESULTS FOR THE $\Delta\varepsilon_{pc}$ TYPE DEFORMATION

Specimen No.	Test Temperature °F	Test Temperature °C	Half Life Axial Strainrange (MM/MM) Total	Elastic	In-elastic	Partitioned Inelastic FPC	Partitioned Inelastic Strain-Range	Half Life Axial Stress Range Maximum (ksi)	Maximum (MN/M^2)	Minimum (ksi)	Minimum (MN/M^2)	Total Elapsed Time to Failure (hours)	Actual Cycles to Failure	Partitioned Cycles to Failure
UNCOATED SPECIMENS														
9U-PC-1	1832	1000	.00944	.00191	.00753	.95	.00715	32.9	226.8	7.0	48.3	3.8	479	528
10U-PC-2	"	"	.01999	.00443	.01556	.86	.01338	69.4	478.6	23.1	159.3	1.0	19	18
12U-PC-4	"	"	.01809	.00445	.01364	.92	.01255	71.1	490.2	22.0	151.7	2.0	30	29
23U-PC-6	"	"	.00386	.00177	.00209	.93	.00194	25.6	176.5	11.4	78.6	16.9	9,810	11,202
26U-PC-8	"	"	.00409	.00169	.00240	.90	.00217	28.4	195.9	7.0	48.3	19.1	10,164	13,733
89U-PC-11	"	"	.00579	.00259	.00319	.85	.00271	39.1	270.3	15.0	103.4	4.9	187	161
94U-PC-14	"	"	.00464	.00246	.00218	.86	.00187	34.7	239.2	16.7	115.2	5.8	418	365
97U-PC-15	"	"	.00292	.00181	.00111	.80	.00089	27.3	188.3	10.5	72.4	26.9	1,978	1,713
28U-PC-9	1600	871	.00856	.00478	.00378	.75	.00283	75.4	519.9	33.5	231.0	2.9	148	127
29U-PC-10	"	"	.00330	.00126	.00204	.80	.00164	24.4	168.3	4.2	29.0	7.4	1,415	1,407
91U-PC-12	"	"	.00659	.00402	.00257	.81	.00209	63.6	438.5	27.8	194.7	5.9	356	312
92U-PC-13	"	"	.01064	.00510	.00554	.83	.00460	80.3	553.7	35.7	246.1	1.1	41	35
98U-PC-16	"	"	.00601	.00343	.00258	.71	.00183	56.6	390.2	21.4	147.6	42.8	396	322
COATED SPECIMENS														
56C-PC-1	1832	1000	.00819	.00348	.00471	.72	.00339	50.5	348.2	22.3	153.8	1.0	55	41
57C-PC-2	"	"	.00450	.00242	.00208	.91	.00189	35.1	242.0	15.4	106.2	8.2	386	355
58C-PC-3	"	"	.00581	.00288	.00293	.87	.00255	43.1	297.2	17.0	117.2	3.9	240	213
93C-PC-8	"	"	.00424	.00257	.00167	.85	.00142	44.2	304.8	9.6	66.2	41.2	691	596
96C-PC-10	"	"	.00585	.00289	.00296	.85	.00252	41.0	282.7	19.3	133.1	5.6	262	229
59C-PC-4	1600	871	.01107	.00535	.00572	.80	.00458	91.2	628.8	30.5	210.3	1.8	63	58
61C-PC-5	"	"	.00774	.00480	.00294	.86	.00252	75.5	520.1	33.7	232.3	6.6	282	261
88C-PC-6	"	"	.00485	.00331	.00154	.80	.00123	47.3	326.2	28.0	193.1	66.0	1,855	1,550
90C-PC-7	"	"	.01055	.00510	.00545	.84	.00457	82.2	566.8	33.9	233.7	2.6	48	43
95C-PC-9	"	"	.00835	.00463	.00372	.91	.00339	71.6	493.6	33.8	233.0	2.8	126	118

TABLE IV

SUMMARY OF RENE' 80 FATIGUE TEST RESULTS FOR THE $\Delta\epsilon_{cp}$ TYPE DEFORMATION

Specimen Number	Test °F	Temperature °C	Half Life Axial Strain Range (MM/MM) Total	Elastic	Inelastic	Partitioned Inelastic FCP	Partitioned Inelastic Strain-range	Half Life Axial Stress Range Maximum (ksi)	Maximum (MN/M²)	Minimum (ksi)	Minimum (MN/M²)	Total Elapsed Time to Failure (hours)	Total Time to to Failure	Partitioned Cycle Failure
Uncoated Specimens														
14U-CP-1	1832	1000	.01595	.00328	.01267	.78	.00987	29.2	201.3	39.4	271.2	.5	12	10
16U-CP-3	"	"	.00589	.00211	.00378	.70	.00264	18.6	128.2	25.4	175.2	7.6	601	512
17U-CP-4	"	"	.00409	.00169	.00240	.88	.00210	11.6	80.0	23.7	163.4	8.6	1,385	1,315
39U-CP-8	"	"	.00436	.00193	.00243	.93	.00227	14.3	98.6	26.1	180.0	8.6	527	497
111U-CP-10	"	"	.00957	.00246	.00711	.75	.00533	18.6	128.2	32.8	226.1	1.0	78	61
30U-CP-5	1600	871	.00736	.00447	.00289	.88	.00254	36.4	251.0	65.4	451.0	1.3	193	184
31U-CP-6	"	"	.00588	.00380	.00208	.97	.00202	28.0	193.1	58.4	402.7	4.7	530	520
36U-CP-7	"	"	.00364	.00253	.00111	.83	.00092	18.6	128.2	39.0	268.9	64.1	3,705	3,435
86U-CP-9	"	"	.00772	.00440	.00332	.92	.00306	31.4	216.5	68.8	474.3	3.4	147	138
112U-CP-11	"	"	.00907	.00512	.00385	.78	.00308	41.3	284.8	75.3	519.2	1.8	101	84
Coated Specimens														
65C-CP-3	1832	1000	.00603	.00284	.00319	.86	.00274	16.8	115.8	42.6	293.7	3.8	251	222
66C-CP-4	"	"	.00966	.00358	.00608	.82	.00498	24.8	171.0	50.0	344.7	1.0	66	58
85C-CP-7	"	"	.00568	.00244	.00324	.77	.00250	21.1	145.5	29.8	205.4	4.5	134	106
87C-CP-8	"	"	.00422	.00223	.00199	.85	.00169	18.0	124.1	28.6	197.2	6.2	950	835
113C-CP-9	"	"	.01023	.00368	.00655	.75	.00491	29.0	200.0	47.9	330.3	1.0	45	36
62C-CP-1	1600	871	.00995	.00498	.00497	.92	.00457	40.0	275.8	73.3	505.4	2.7	150	151
64C-CP-2	"	"	.00490	.00358	.00132	.88	.00116	34.9	240.6	46.7	322.0	33.6	1,818	1,630
83C-CP-5	"	"	.00709	.00464	.00245	.86	.00210	28.7	198.0	77.0	530.9	12.1	455	406
84C-CP-6	"	"	.01145	.00616	.00529	.82	.00433	52.0	358.5	88.2	608.1	1.5	29	25
115C-CP-11	"	"	.00907	.00533	.00374	.91	.00340	49.4	340.6	71.9	495.7	1.0	77	71

TABLE V

SUMMARY OF RENE' 80 FATIGUE TEST RESULTS FOR THE $\Delta\varepsilon_{cc}$ TYPE DEFORMATION

Specimen Number	Temperature °F	Temperature °C	Half Life Axial Strain Range (MM/MM) Total	Elastic	Inelastic	Partitioned Inelastic FCC	Strain-Range	FPP	Strain-Range	FPC	Strain-Range	Half Life Axial Stress Range Maximum (ksi)	Maximum (MN/M²)	Minimum (ksi)	Minimum (MN/M²)	Total Elapsed Time to Failure	Actual Cycles to Failure	Partitioned Cycles to Failure
UNCOATED SPECIMENS																		
19U-CC-3	1832	1000	.00457	.00159	.00298	.70	.00209	.20	.00060	.10	.00029	18.7	128.9	14.5	100.0	51.0	420	466
20U-CC-4	"	"	.00233	.00099	.00134	.85	.00114	.10	.00013	.05	.00007	12.4	85.5	8.2	56.5	70.5	8,154	11,993
40U-CC-5	"	"	.00273	.00118	.00155	.75	.00116	.20	.00031	.05	.00008	14.6	100.7	9.8	68.3	152.6	4,783	6,043
67U-CC-6	"	"	.00599	.00093	.00506	.75	.00380	.20	.0010	.05	.00025	11.7	80.7	7.8	53.8	24.8	257	267
119U-CC-11	"	"	.00973	.00251	.00722	.85	.00614	.11	.00079	.04	.00029	27.1	186.9	25.3	174.5	2.6	69	70
71U-CC-7	1600	871	.01368	.00405	.00963	.68	.00655	.25	.00241	.07	.00067	50.9	351.0	41.4	285.5	1.6	26	33
73U-CC-8	"	"	.01193	.00424	.00769	.78	.00600	.11	.00085	.11	.00084	50.0	344.7	46.5	320.7	2.2	35	56
76U-CC-9	"	"	.00784	.00340	.00444	.90	.00400	.03	.00013	.07	.00031	41.9	289.0	35.6	245.4	17.6	166	215
79U-CC-10	"	"	.00507	.00263	.00244	.84	.00205	.12	.00029	.04	.00010	32.3	222.7	27.5	189.7	53.1	637	607
120U-CC-12	"	"	.00622	.00267	.00355	.78	.00277	.20	.00071	.02	.00007	30.9	213.0	29.9	206.1	6.6	181	158
COATED SPECIMENS																		
68C-CC-1	1832	1000	.01135	.00269	.00865	.85	.00736	.08	.00069	.07	.00060	30.3	208.9	26.0	179.3	1.1	17	16
81C-CC-6	"	"	.00790	.00228	.00562	.68	.00384	.08	.00045	.24	.00133	25.9	178.6	21.8	150.3	3.8	76	99
82C-CC-7	"	"	.00445	.00191	.00254	.88	.00223	.06	.00015	.06	.00016	22.5	155.2	17.5	120.7	42.9	621	654
116C-CC-8	"	"	.00754	.00239	.00515	.89	.00458	.06	.00031	.05	.00026*	28.4	195.9	21.6	148.9	4.2	77	78
117C-CC-9	"	"	.00555	.00210	.00345	.75	.00259	.20	.00069	.05	.00017	23.3	160.7	20.5	141.4	12.0	225	233
69C-CC-2	1600	871	.01005	.00420	.00585	.73	.00427	.17	.00099	.10	.00059	49.6	341.9	46.0	317.2	6.0	108	204
72C-CC-3	"	"	.01377	.00543	.00834	.79	.00659	.15	.00125	.06	.00050	64.7	446.1	59.0	406.8	2.5	33	52
78C-CC-4	"	"	.00917	.00413	.00504	.69	.00348	.14	.00071	.17	.00085	50.4	347.5	43.7	301.3	6.7	109	192
80C-CC-5	"	"	.00824	.00404	.00420	.93	.00390	.04	.00017	.03	.00013*	48.3	333.0	43.6	300.6	18.6	171	223
118C-CC-10	"	"	.00582	.00316	.00266	.75	.00200	.19	.00050	.06	.00016	38.2	263.4	33.7	232.3	31.7	554	615

* Partitioned Inelastic $\Delta\varepsilon_{cp}$ Deformation

TABLE VI

SUMMARY OF RENÉ 80 FATIGUE RESULTS FOR $\Delta\varepsilon_{pp}$ TESTS CONDUCTED ON UNCOATED MATERIAL IN POORER VACUUM (APPROXIMATELY 10^{-6} TORR)

Specimen Number	Temperature °F	Temperature °C	Half-Life Axial Strain Range (MM/MM) Total	Elastic	Inelastic	Partitioned Inelastic	Half-Life Axial Stress Range Maximum (ksi)	Maximum (MN/M^2)	Minimum (ksi)	Minimum (MN/M^2)	Total Elapsed Time to Failure (Hours)	Actual Cycles to Failure
99U-PP-14	Room	Room	.00639	.00568	.00071	Fpp = 1	91.2	628.8	79.1	545.4	2.0	6,900
110U-PP-25	Room	Room	.00979	.00828	.00151	Fpp = 1	117.5	810.2	130.6	900.4	0.5	1,306
101U-PP-16	400	204	.00741	.00667	.00074	Fpp = 1	97.0	668.8	96.1	662.6	0.5	1,674
102U-PP-17	"	"	.00769	.00698	.00071	Fpp = 1	97.7	674.3	103.3	712.3	0.6	2,170
1U-PP-1*	1000	538	.00874	.00773	.00101	Fpp = 1	96.3	664	106.7	735.6	0.6	1,621
2U-PP-2*	"	"	.00747	.00654	.00093	Fpp = 1	82.4	568.2	89.3	615.7	0.5	1,950
105U-PP-20	1200	649	.00784	.00669	.00115	Fpp = 1	83.6	576.4	85.5	589.6	0.2	744
107U-PP-22	"	"	.00642	.00539	.00103	Fpp = 1	71.9	495.7	64.5	444.8	1.3	4,402
103U-PP-18	1400	760	.00604	.00488	.00116	Fpp = 1	61.5	424.1	56.3	388.2	1.2	4,216
104U-PP-19	"	"	.00792	.00663	.00129	Fpp = 1	77.8	536.4	82.4	568.2	0.1	496
108U-PP-23	1832	1000	.00343	.00204	.00139	Fpp = 1	22.7	156.5	20.0	137.9	1.6	5,766
109U-PP-24	"	"	.00576	.00280	.00296	Fpp = 1	30.6	210.9	27.9	192.4	0.3	1,240

* This test conducted in ultra-high vacuum, approximately 10^{-7} and below.

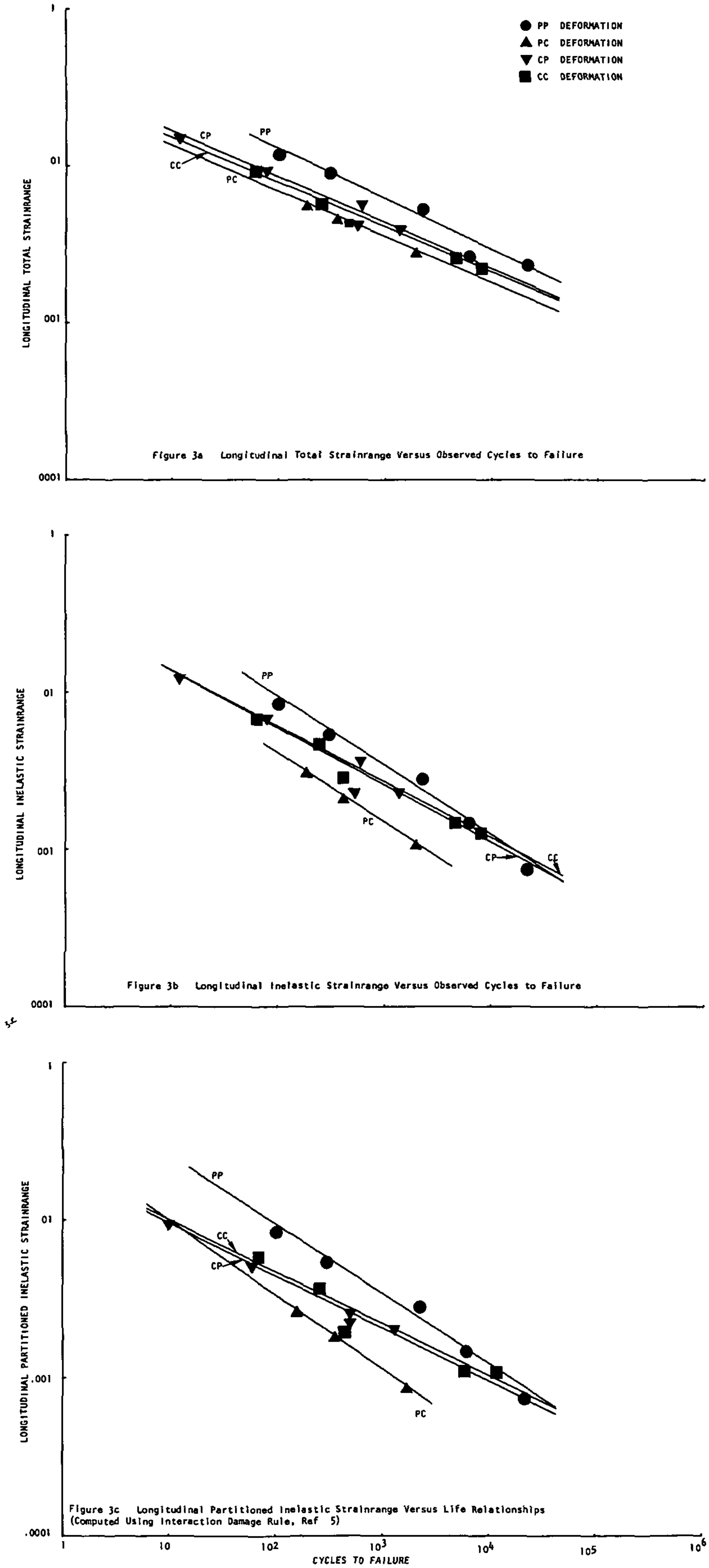


Figure 3. Rene' 80 Fatigue Test Results at 1000°C (1832°F) in the Uncoated Condition.

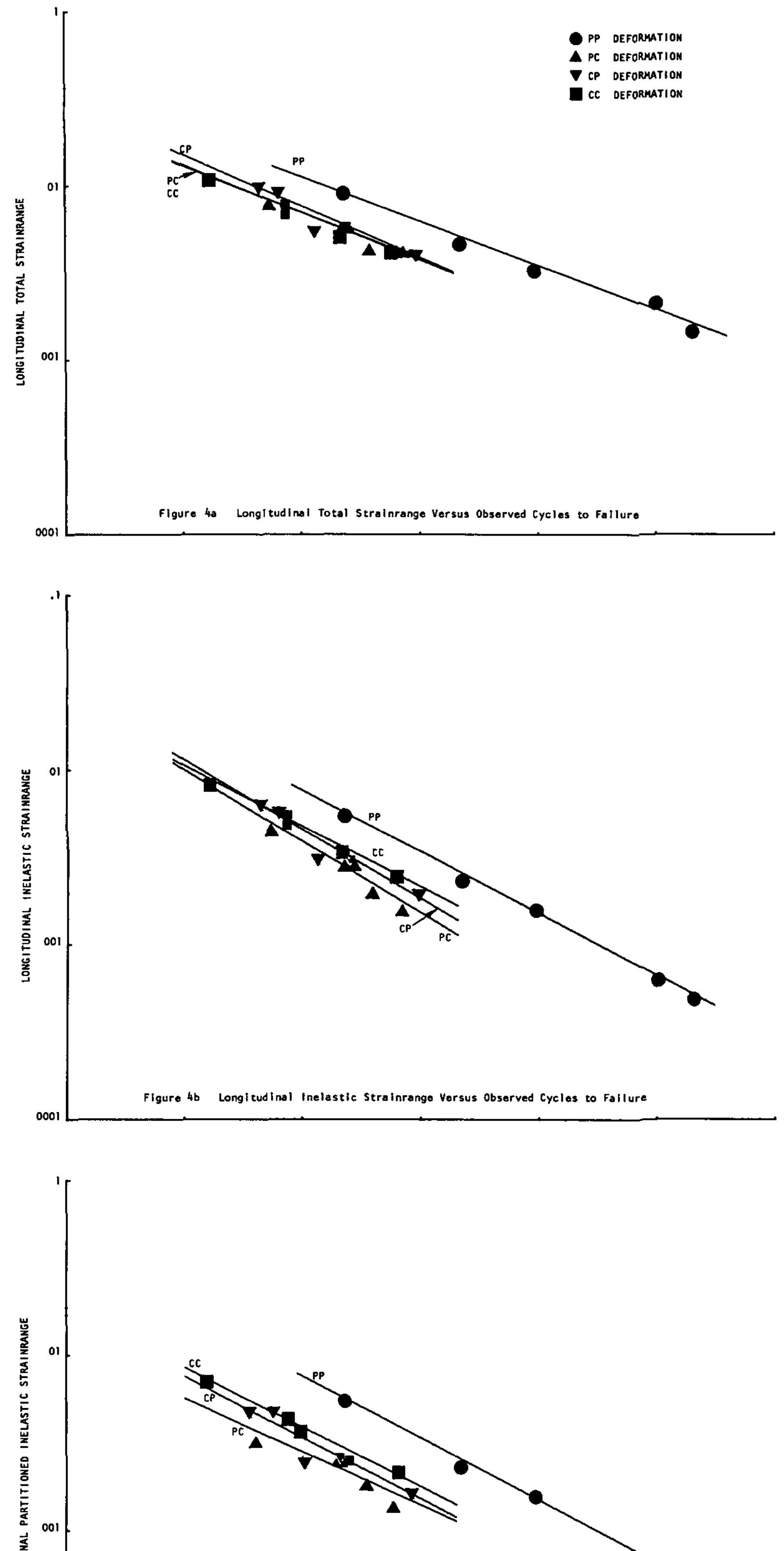


Figure 4a Longitudinal Total Strainrange Versus Observed Cycles to Failure

Figure 4b Longitudinal Inelastic Strainrange Versus Observed Cycles to Failure

Figure 4c Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref 5)

Figure 4. Rene' 80 Fatigue Test Results at 1000°C (1832°F) in the Coated Condition.

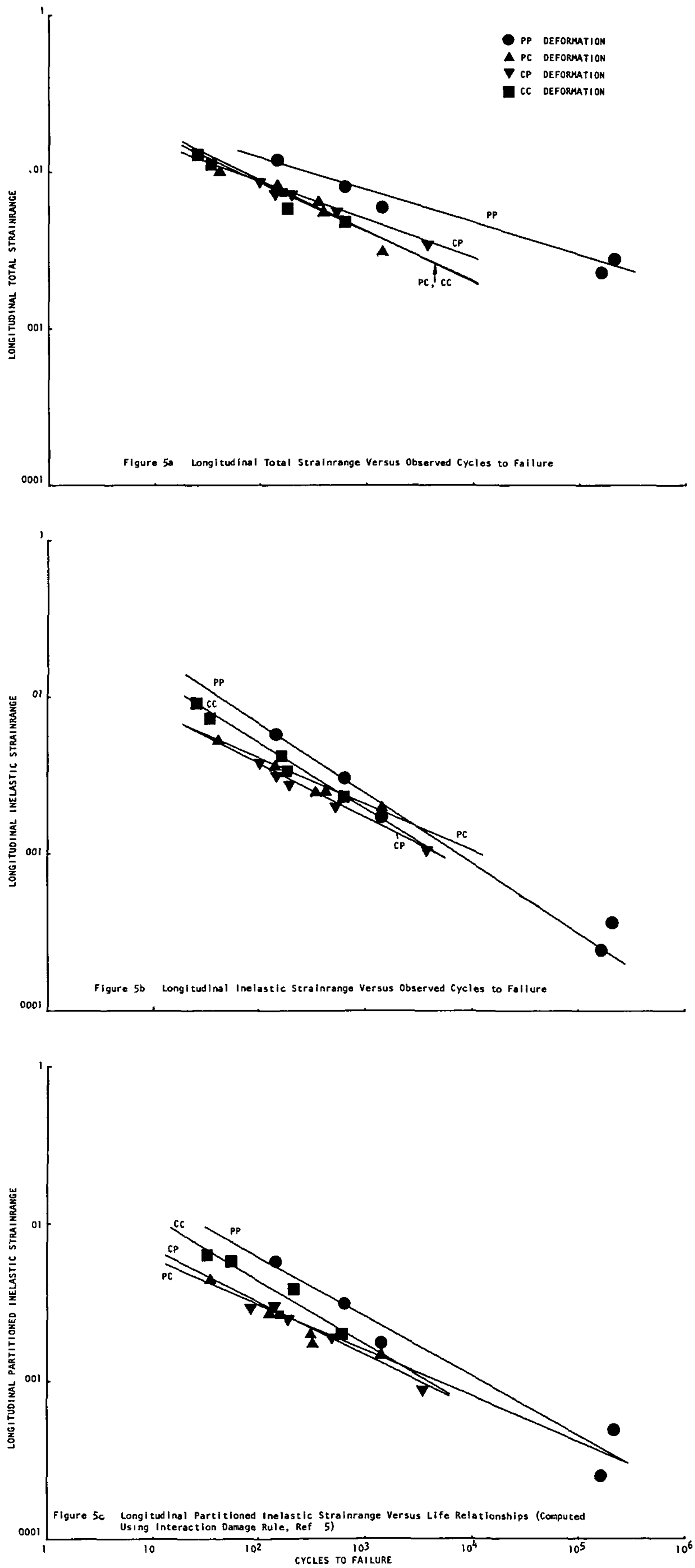


Figure 5a Longitudinal Total Strainrange Versus Observed Cycles to Failure

Figure 5b Longitudinal Inelastic Strainrange Versus Observed Cycles to Failure

Figure 5c Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref 5)

Figure 5. Rene' 80 Fatigue Test Results at 871°C (1600°F) in the Uncoated Condition.

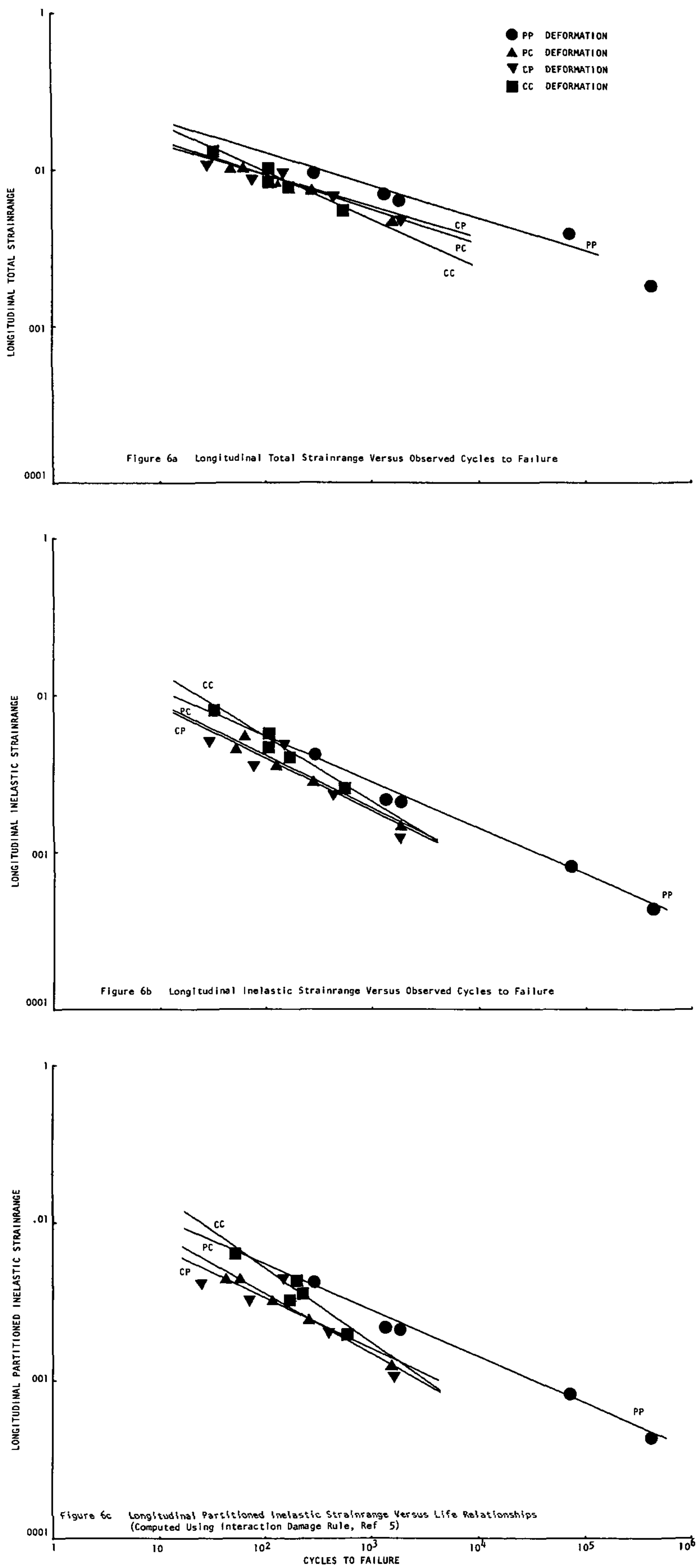


Figure 6. Rene' 80 Fatigue Test Results at 871°C (1600°F) in the Coated Condition.

For tests conducted at 1000°C (1832°F), Figures 3 and 4, the results indicate that the relative positions of the failure lives for the four basic types of strainrange components (PP, PC, CP and CC) changes little as a result of the presence of the aluminide coating. In all instances PP deformation was the least damaging while PC deformation was the most damaging by approximately an order of magnitude difference in number of cycles to failure. The CP and CC lines were quite close together and fell between the PC and PP lines, ranging from 2/3 to 1/2 order of magnitude below the PP line. A difference was observed between coated and uncoated material, however, in that for the values of inelastic and partitioned inelastic strainrange included in this study for uncoated material, the lines for CP and CC approached the PP line at the low strainrange values, Figures 3b and 3c.

Results of tests conducted at 871°C (1600°F), Figures 5 and 6, were consistent with those conducted at 1000°C (1832°F) in that the aluminide coating had little effect on the relative positions of the failure lives for the four basic types of strainrange components. In all cases PP deformation was the least damaging. Unlike the 1000°C (1832°F) results, however, the PC and CP lines were both comparable, ranging from 1/2 to 1 order of magnitude below the PP line. In terms of total and inelastic strainrange, the CC results were somewhat comparable to those for PC and CP, but the partitioned inelastic strainrange results indicated that CC was less damaging than PC and CP by approximately 1/2 order of magnitude at the higher strainrange values. Manson and Halford have made an analysis utilizing Strainrange Partitioning (6) of the low cycle fatigue data generated independently by Lord and Coffin on uncoated Rene' 80 at 871°C (1600°F). They determined that the partitioned lives for the 0.0032 strainrange at this temperature were N_{pp} = 600, N_{cp} = 450, N_{cc} = 190 and N_{pc} = 80. With the exception of the N_{cp} results, these values agree quite closely with the data presented in Figure 5c. This indicates that the Method of Strainrange Partitioning may have some potential as a unifying framework around which the many factors concerning fatigue at elevated temperatures can be coherently structured.

In order to illustrate the effect of temperature and coating on these fatigue results in a more graphic manner, the results for each of the basic types of deformation have been plotted separately in Figures 7-10 in terms of total strainrange versus observed cycles to failure and partitioned inelastic strainrange versus life relationship computed using the interaction damage rule (5). For each of these plots a least squares fit was made of all the data. These least squares lines suggest that for all four basic types of deformation, there was little difference between coated and uncoated material at 1000°C (1832°F) and 871°C (1600°F) and further, that there was little effect of temperature on the fatigue results. These results were not unexpected in that the ultrahigh vacuum test atmosphere nullified the effect of oxidation behavior thus minimizing possible differences in fatigue behavior.

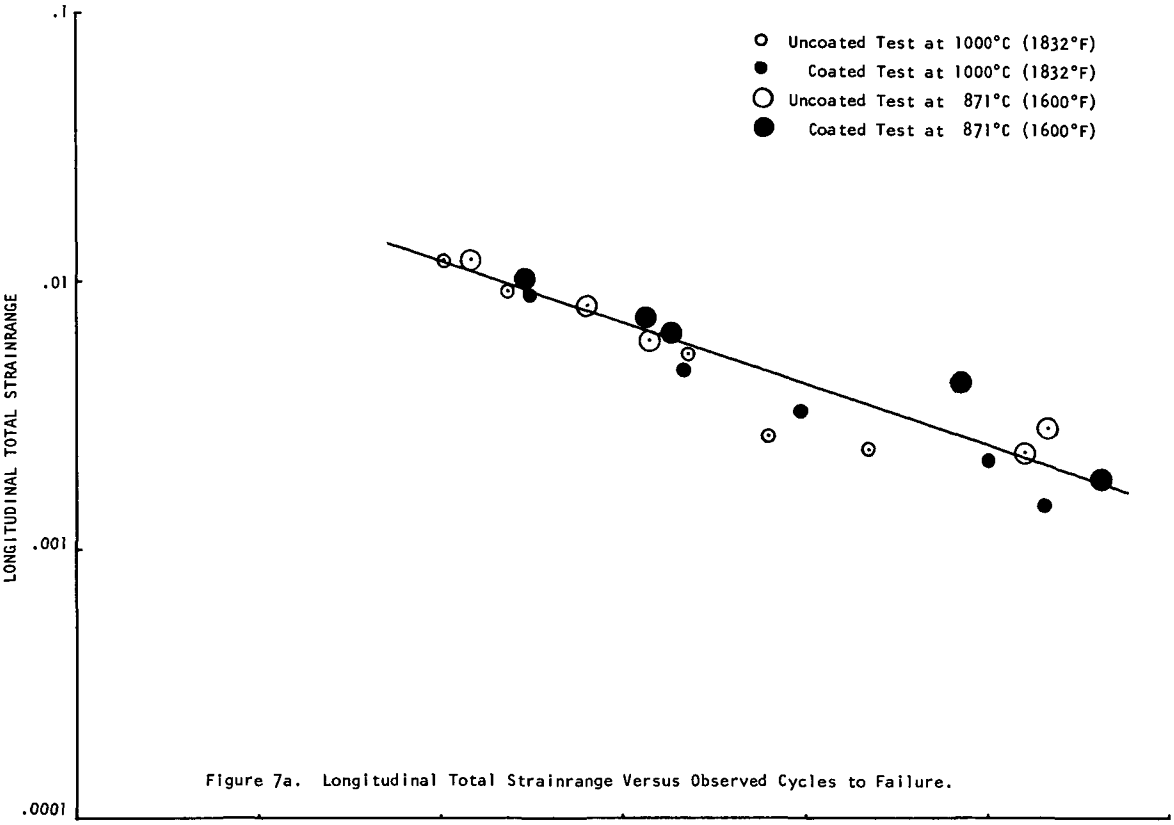


Figure 7a. Longitudinal Total Strainrange Versus Observed Cycles to Failure.

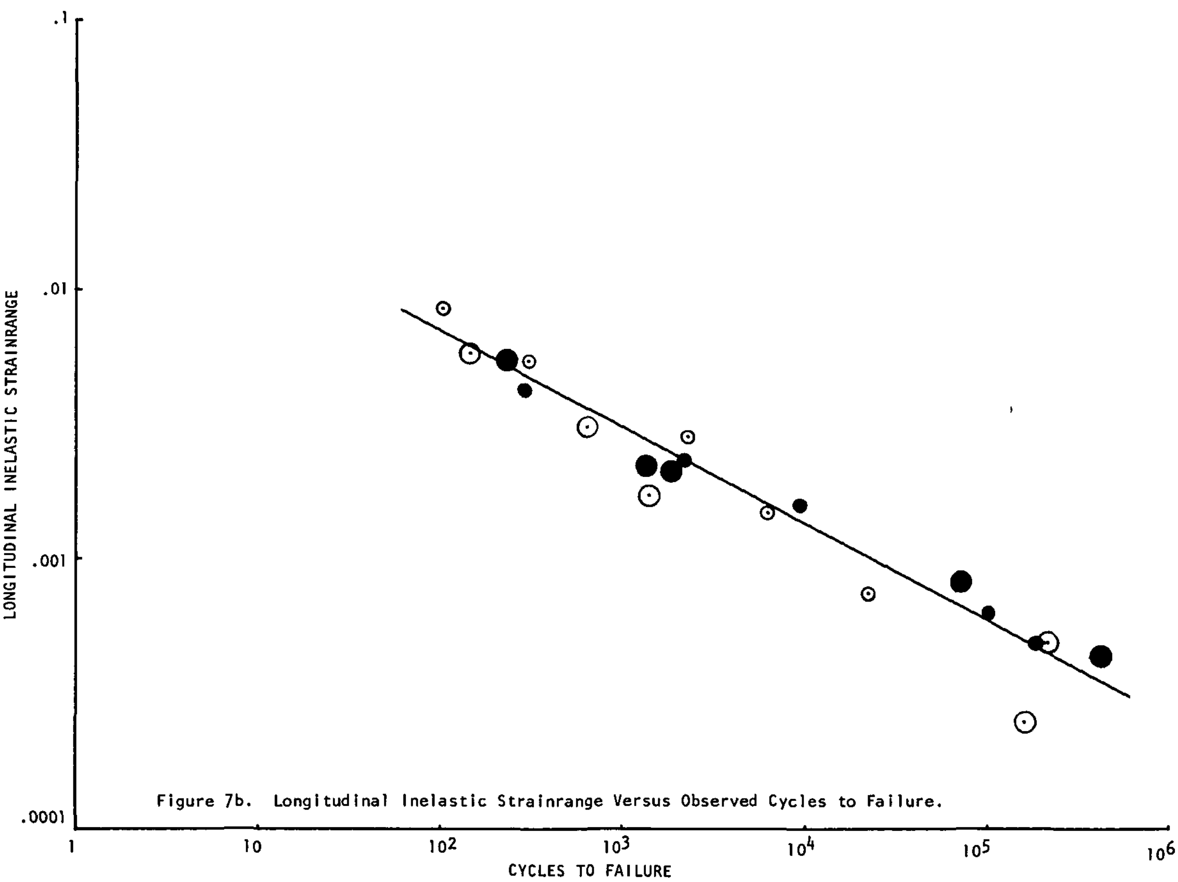


Figure 7b. Longitudinal Inelastic Strainrange Versus Observed Cycles to Failure.

Figure 7. Rene' 80 Fatigue Test Results at 1000°C (1832°F) and 871°C (1600°F) for Uncoated and Coated Specimens Tested with the $\Delta\varepsilon_{pp}$ Type Deformation.

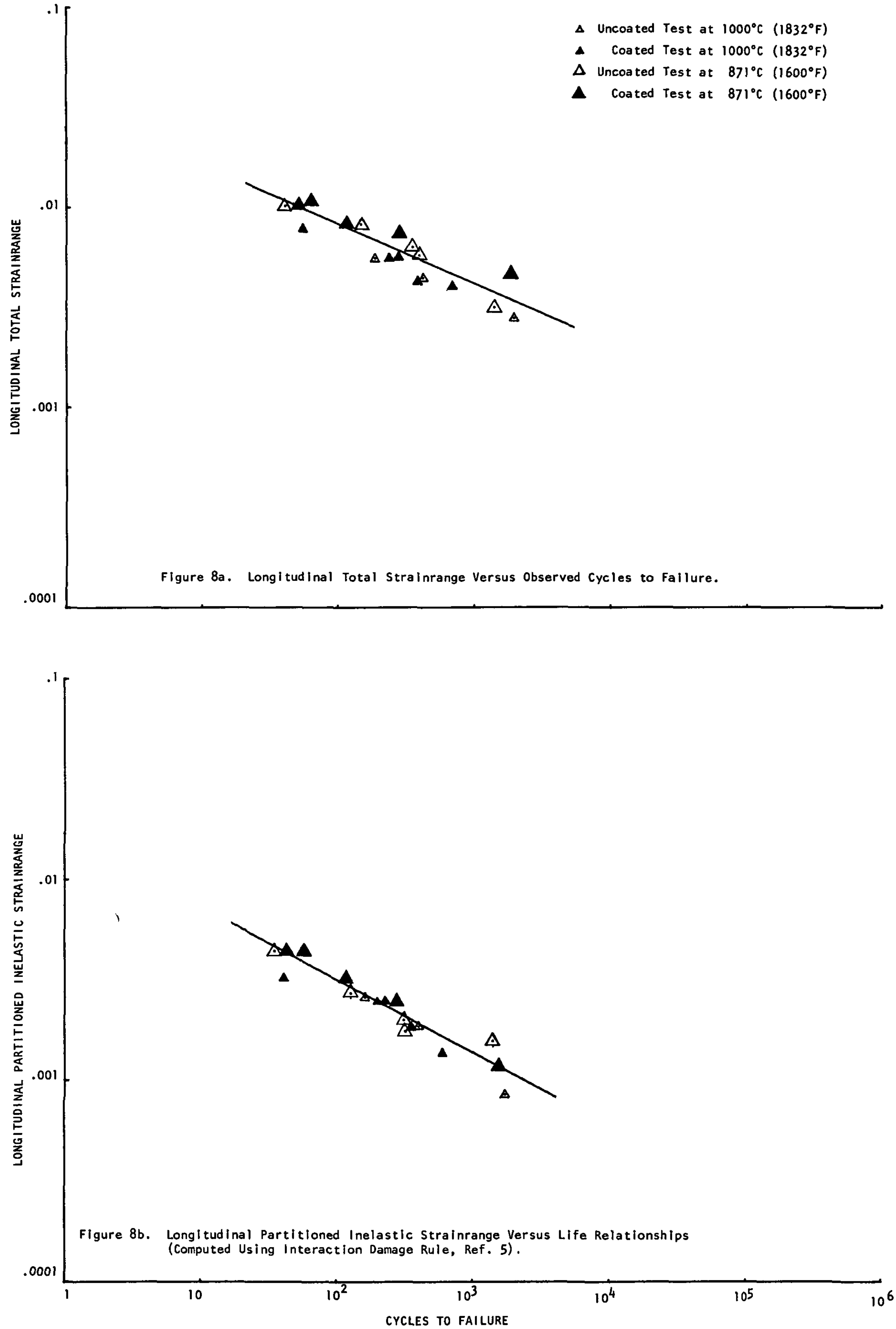


Figure 8a. Longitudinal Total Strainrange Versus Observed Cycles to Failure.

Figure 8b. Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref. 5).

Figure 8. Rene' 80 Fatigue Test Results at 1000°C (1832°F) and 871°C (1600°F) for Uncoated and Coated Specimens Tested with the $\Delta\varepsilon_{pc}$ Type Deformation.

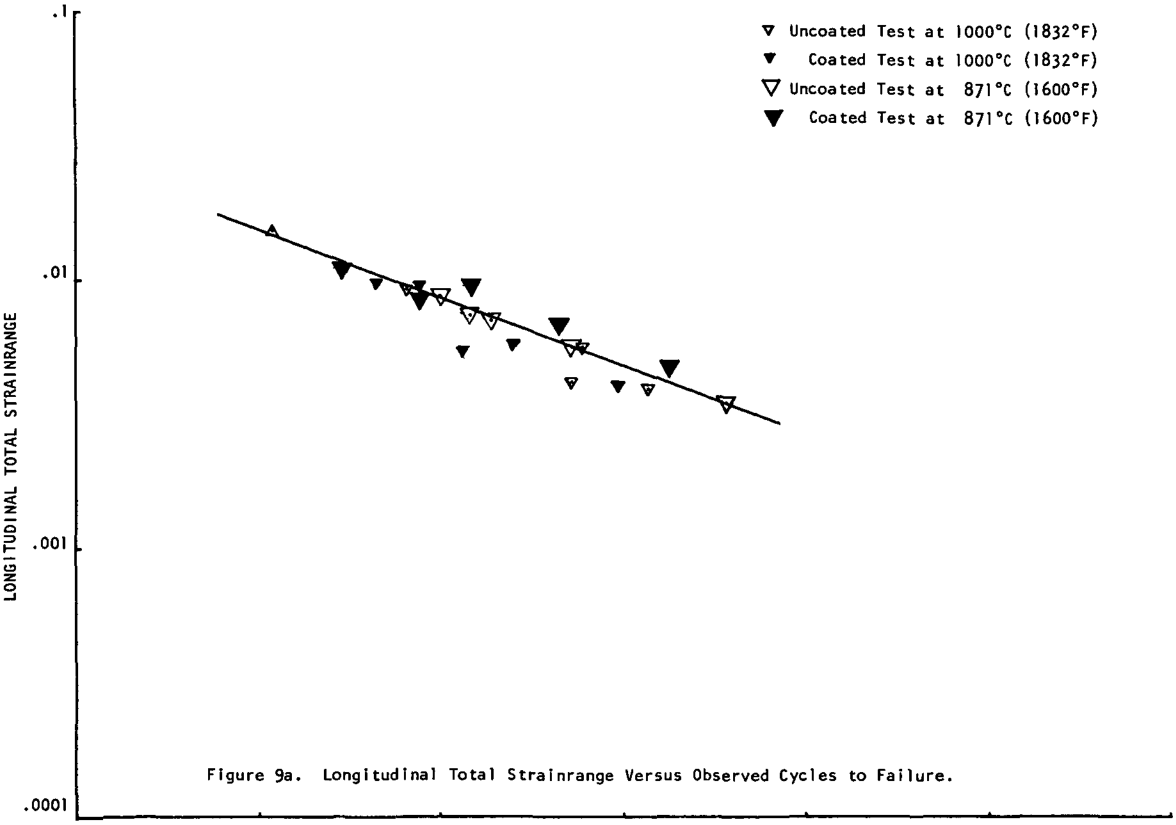


Figure 9a. Longitudinal Total Strainrange Versus Observed Cycles to Failure.

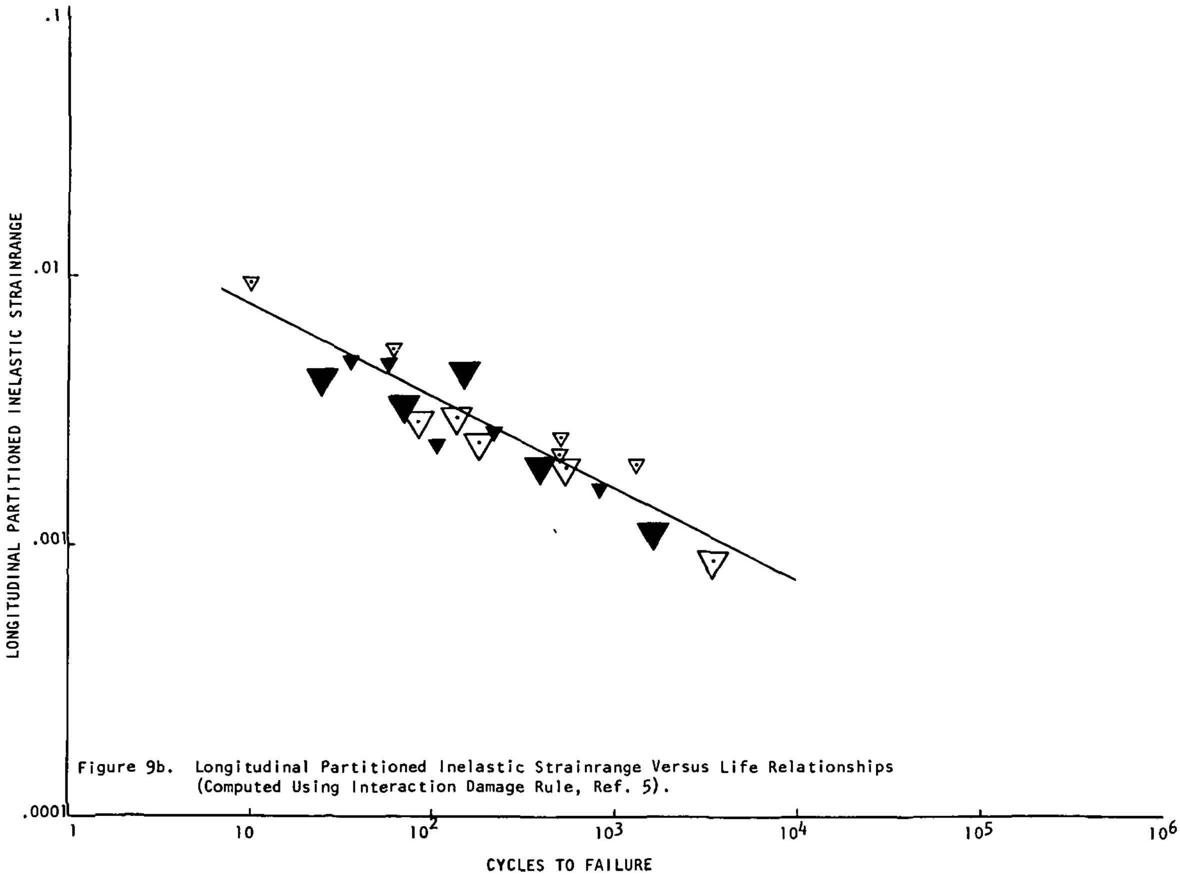


Figure 9b. Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref. 5).

Figure 9. Rene' 80 Fatigue Test Results at 1000°C (1832°F) and 871°C (1600°F) for Uncoated and Coated Specimens Tested with the $\Delta\varepsilon_{cp}$ Type Deformation

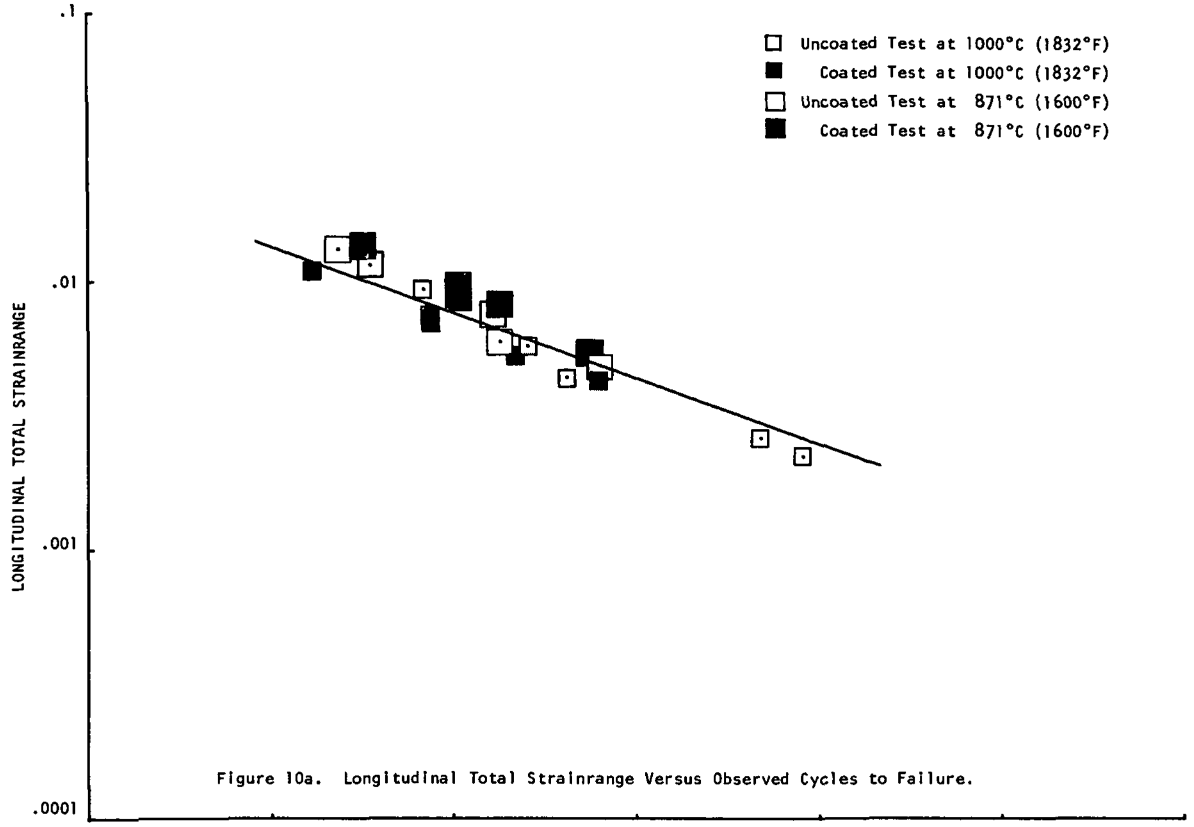


Figure 10a. Longitudinal Total Strainrange Versus Observed Cycles to Failure.

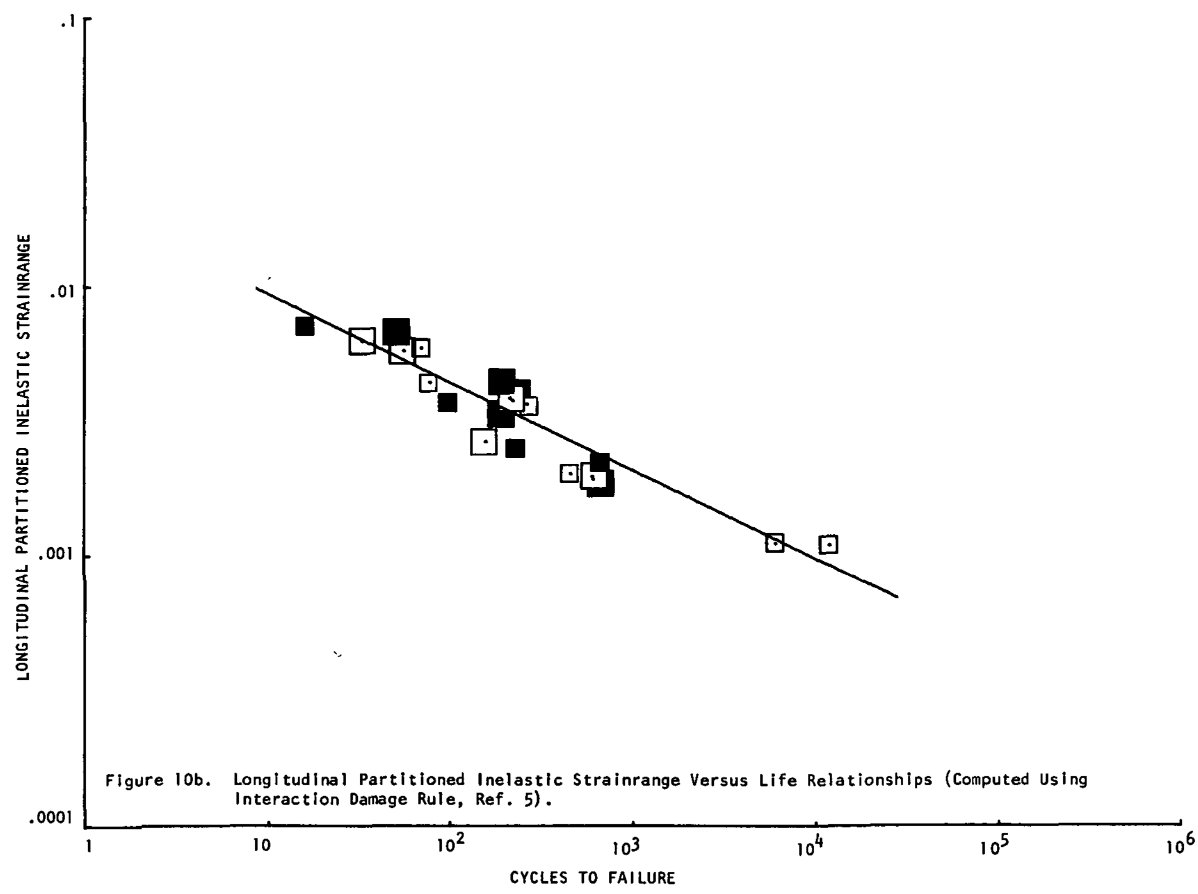


Figure 10b. Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref. 5).

Figure 10. Rene' 80 Fatigue Test Results at 1000°C (1832°F) and 871°C (1600°F) for Uncoated and Coated Specimens Tested with the $\Delta\varepsilon_{cc}$ Type Deformation.

To summarize these fatigue results more clearly, the least squares lines shown in Figures 7-10 are included in the composite plot of Figure 11. These results indicate that PP deformation resulted in the least damaging type of cycling. When a time-dependent creep component was introduced into the cycle, however, an effect was observed which was dependent upon which portion of the cycle contained the creep component. The PC type deformation, in which creep was introduced in the compressive portion of the cycle, was most damaging, resulting in failure lives one order of magnitude below those for PP deformation. The CP type deformation, in which creep was introduced in the tensile portion of the cycle resulted in failure lives slightly higher than those for PC, i.e., slightly less than an order of magnitude below those for PP. The least damaging of the creep type cycling was CC in which creep occurred both in the tensile and compressive portions of the cycle. It resulted in failure lives approximately 1/2 an order of magnitude below those for PP.

The life results from Table VI for tests conducted at a number of different temperatures on uncoated material with the PP type deformation in a poorer vacuum (approximately 10^{-6} torr) are shown in Figure 12. This figure contains a plot of total strainrange versus observed cycles to failure and inelastic strainrange versus observed cycles to failure. No tests were conducted under these conditions at 871°C (1600°F) but the least squares lines from Figure 5 for the ultrahigh vacuum tests have been included for comparative purposes. The results for inelastic strainrange indicate a decrease in fatigue life as temperature is reduced. It has been generally acknowledged that in the absence of time dependent deformation (creep) a material's ductility will be an indicator of its relative fatigue resistance with a decrease in ductility usually resulting in a decrease in fatigue life (7). Ductility results for cast Rene' 80 indicate a decrease with temperature from 1000°C (1832°F) (8). Thus, the inelastic strainrange results for Rene' 80 do reflect the decrease in fatigue life with decreasing ductility.

B. Microstructural Observations

All the fatigue specimens failed within the hourglass areas. There was no evidence of the specimen geometry change known as "barrelling" which is characterized by an increase in specimen diameter adjacent to the center of the original hourglass configuration. This effect has been observed in 304 stainless steel (9) and tantalum base materials (3). Metallographic examination was conducted on selected specimens and included light and scanning electron microscopy to aid in the interpretation of the fatigue results. The results indicated that microstructural damage varied with cycle type, test temperature and surface condition (coated versus uncoated), Figures 13-18.

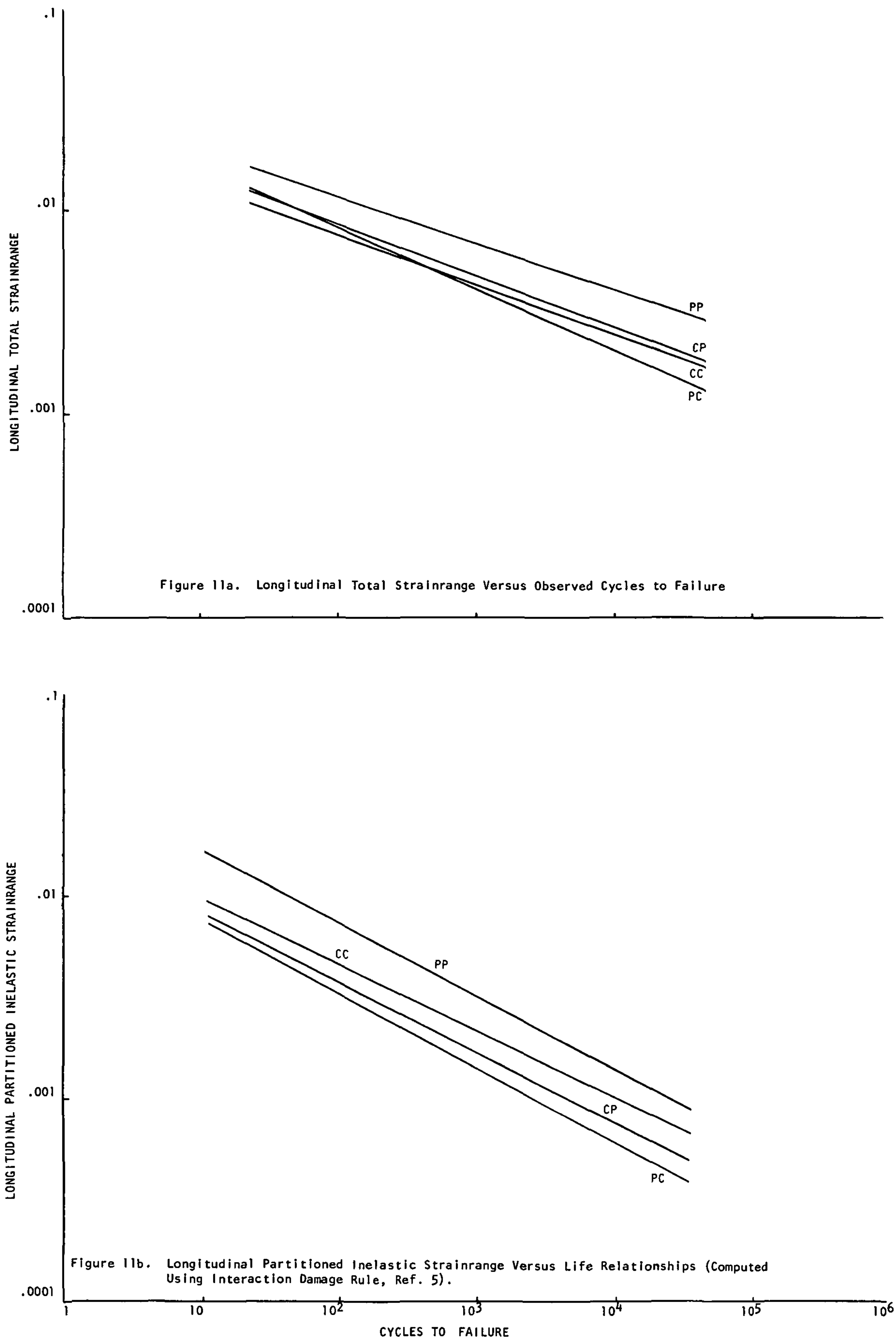


Figure 11a. Longitudinal Total Strainrange Versus Observed Cycles to Failure

Figure 11b. Longitudinal Partitioned Inelastic Strainrange Versus Life Relationships (Computed Using Interaction Damage Rule, Ref. 5).

Figure 11. Composite Plot of Least Squares Lines Through Fatigue Data Shown in Figures 7-10.

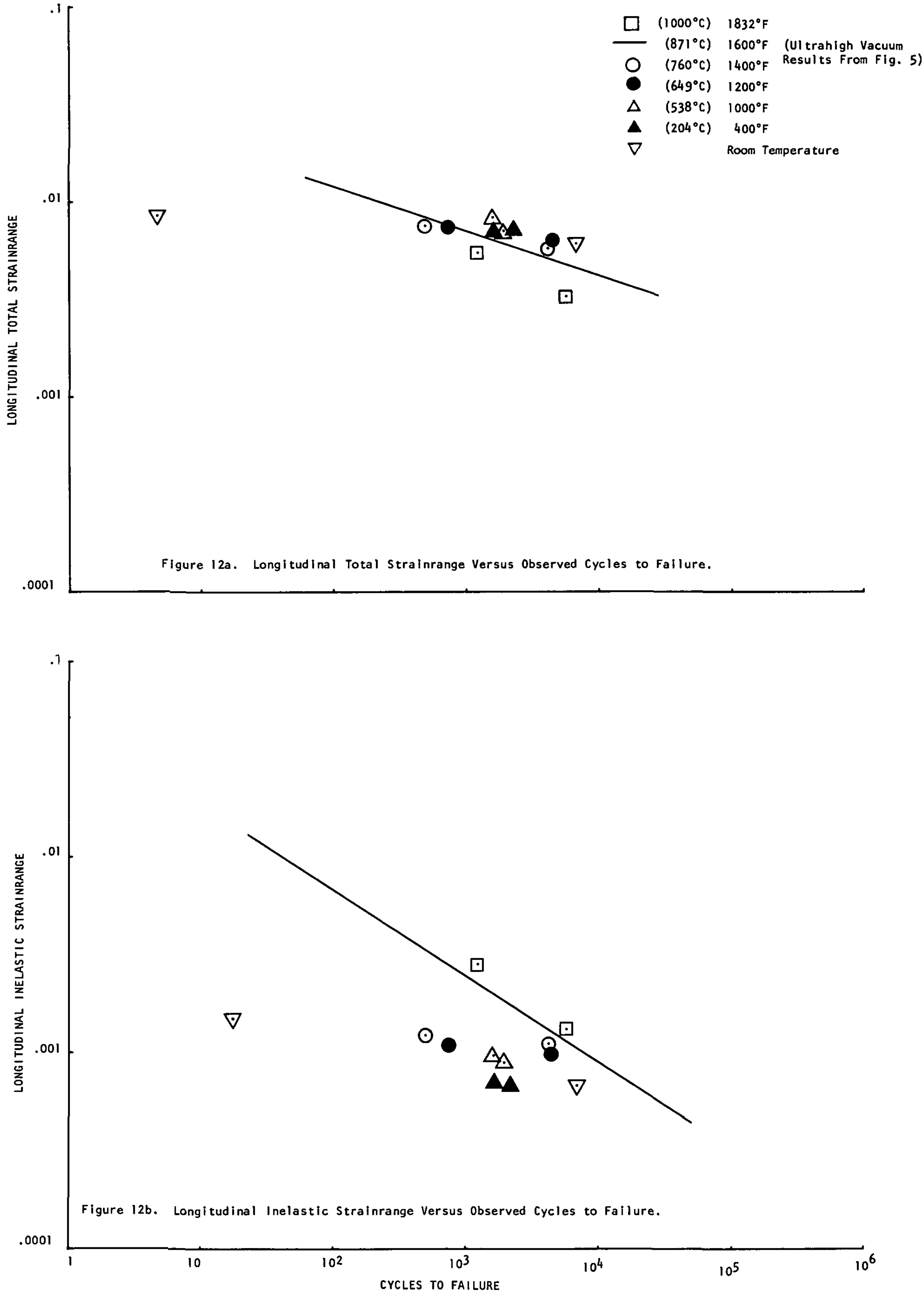
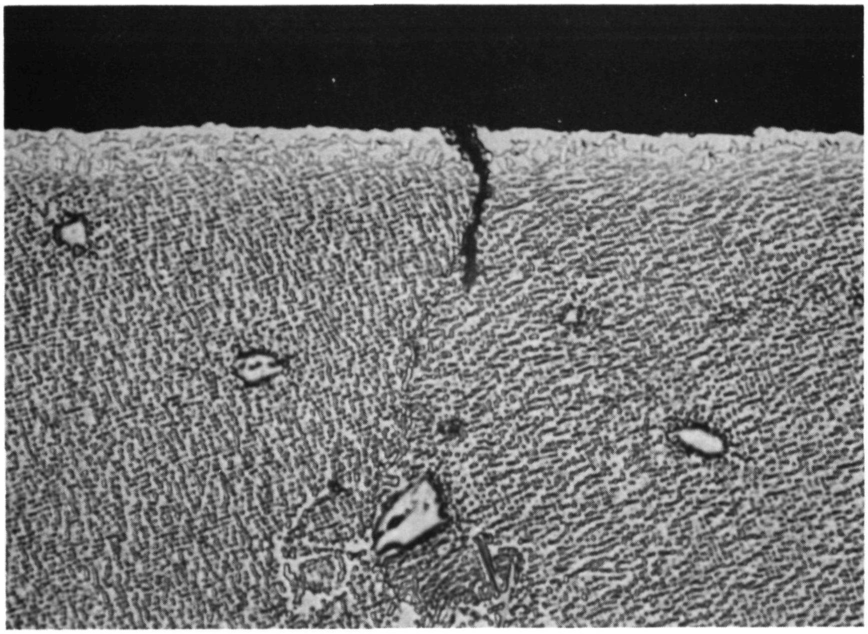


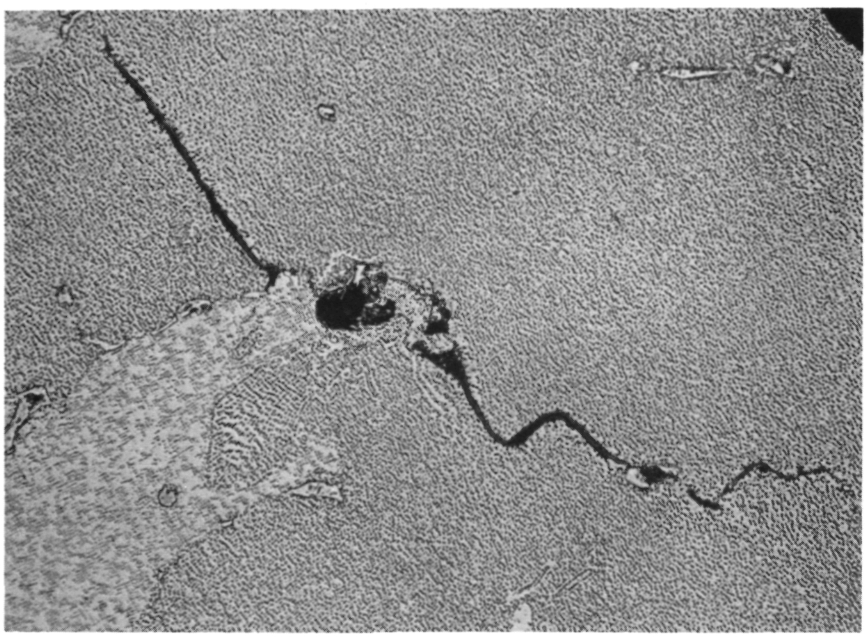
Figure 12a. Longitudinal Total Strainrange Versus Observed Cycles to Failure.

Figure 12b. Longitudinal Inelastic Strainrange Versus Observed Cycles to Failure.

Figure 12. Rene' 80 Fatigue Test Results at Various Temperatures for Uncoated Material Tested in Poorer Vacuum (Approximately 10^{-6} Torr) with the $\Delta\varepsilon_{pp}$ Type Deformation.

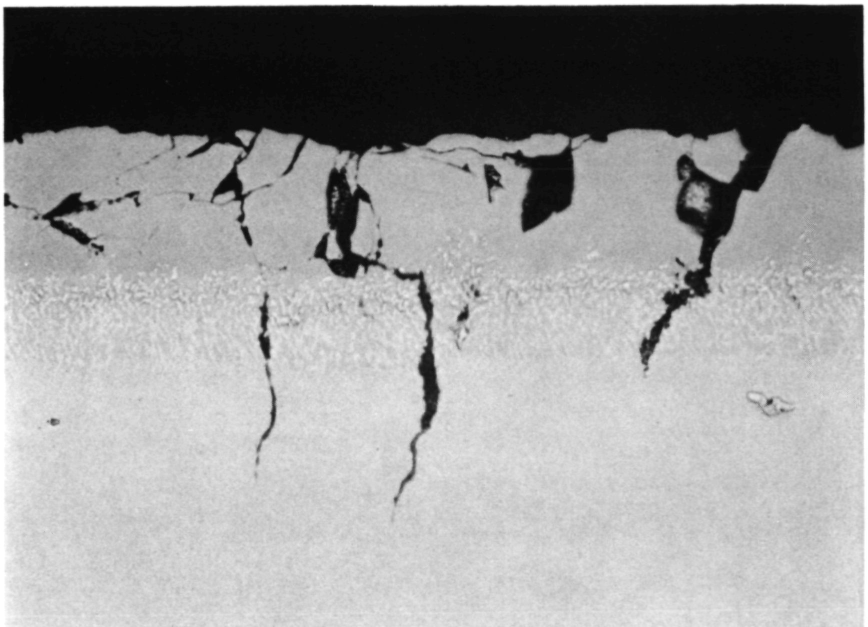


a) Surface Grain Boundary Crack Initiation with Crack Branching Off Into Matrix Region, 800X Magnification.

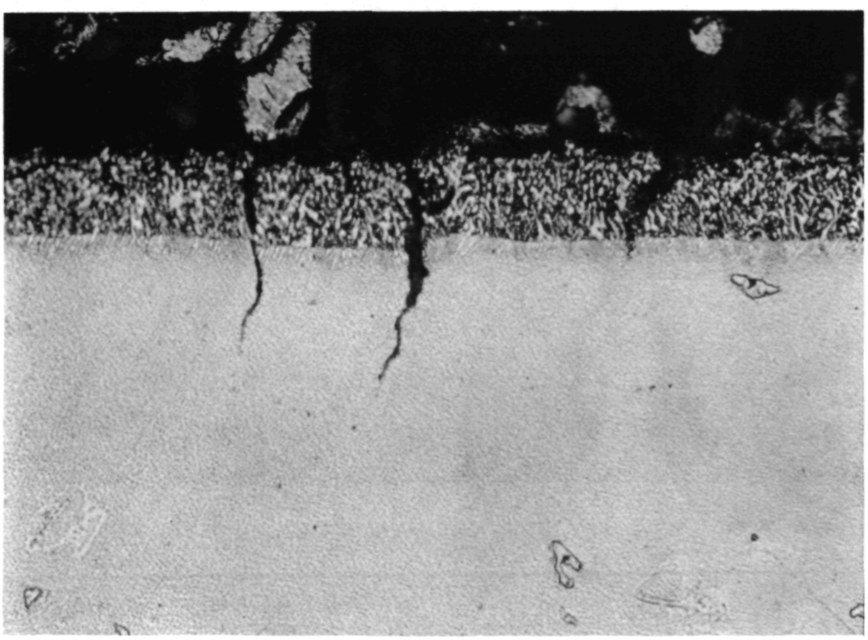


b) Grain Boundary Porosity Crack Initiation with Crack Branching Off Into Matrix Region, 400X Magnification.

Figure 13. Light photomicrographs of fatigue specimen 8U-PP-7, tested at 1000°C (1832°F), 1.033 Hz, total strainrange of 0.00247. Failure occurred after 22,115 cycles. Fry's etch.

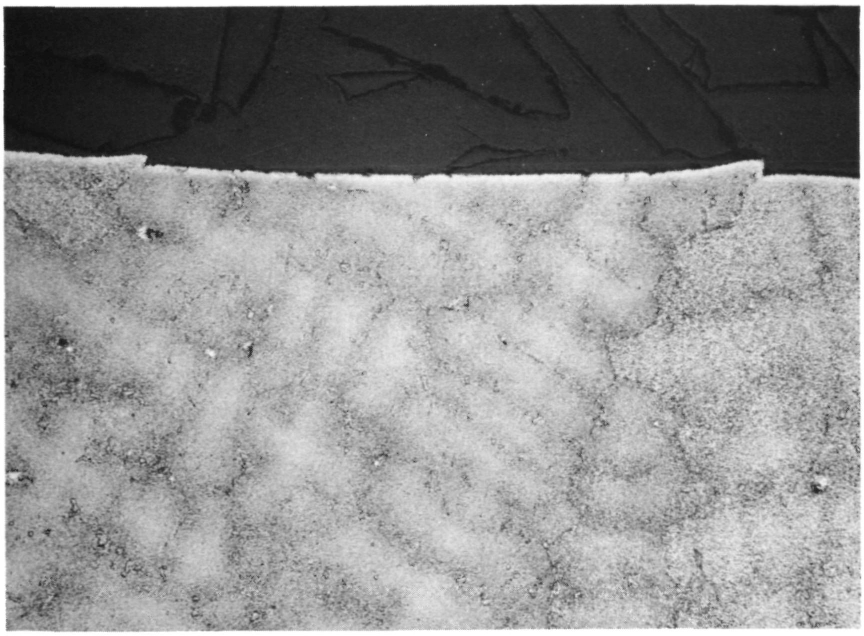


a) Unetched

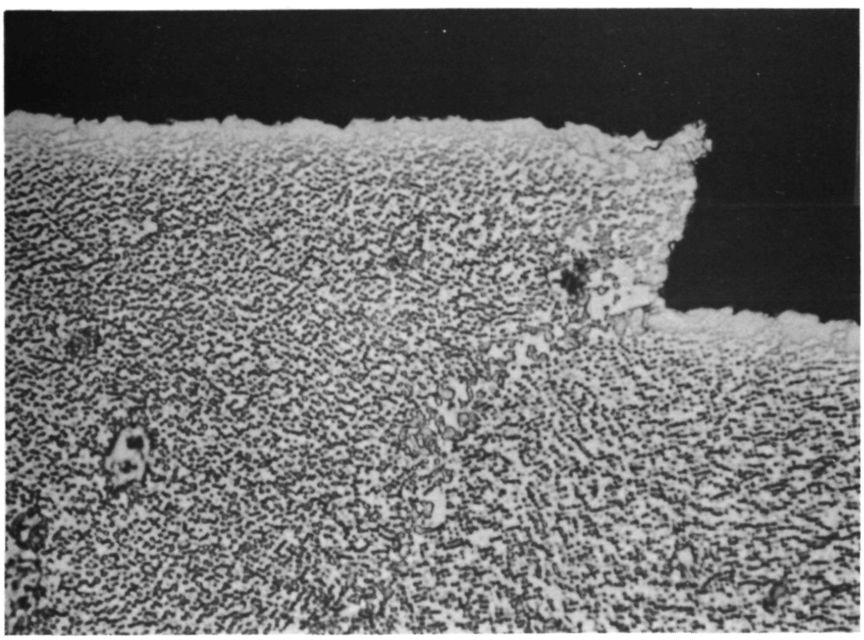


b) Fry's etch

Figure 14. Light photomicrographs of fatigue specimen 51C-PP-6, tested at 871°C (1600°F), total strainrange of 0.00672. Failure occurred after 1860 cycles. Note coating cracks propagating transgranularly into specimen, 500X magnification.

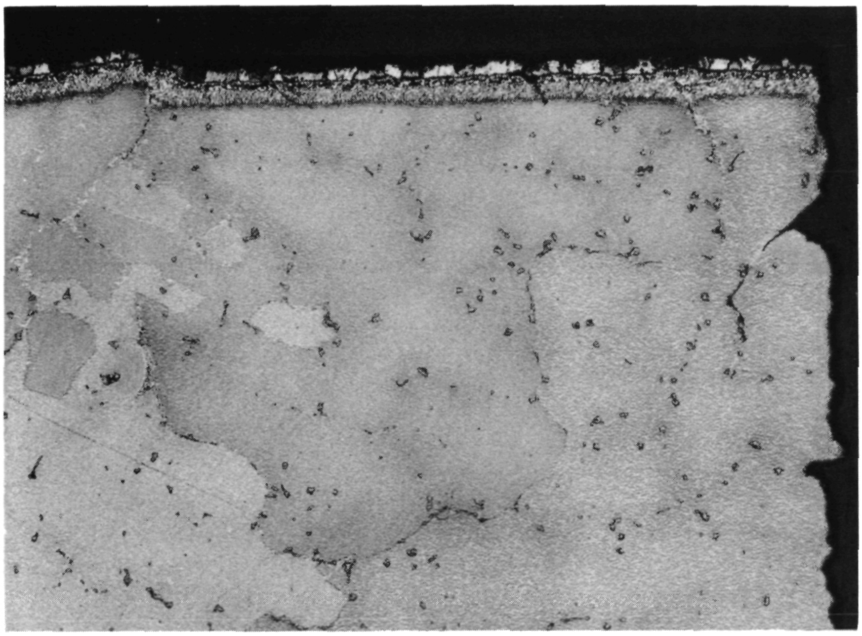


a) 80X Magnification

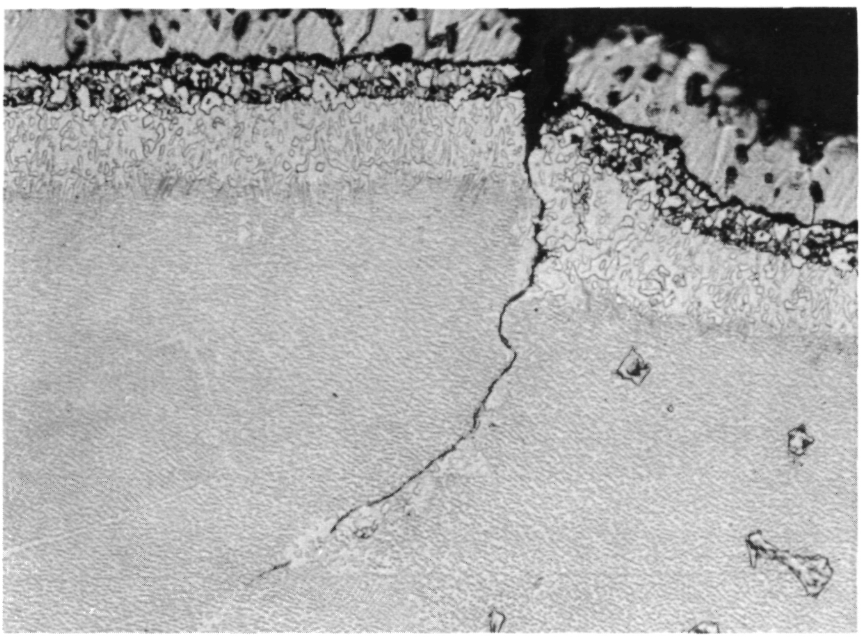


b) 800X Magnification

Figure 15. Light photomicrographs of uncoated fatigue specimen 10U-PC-2, tested at 1000°C (1832°F), total strainrange of 0.01999. Failure occurred after 19 cycles. Note grain extrusion as a result of PC deformation. Fry's etch.

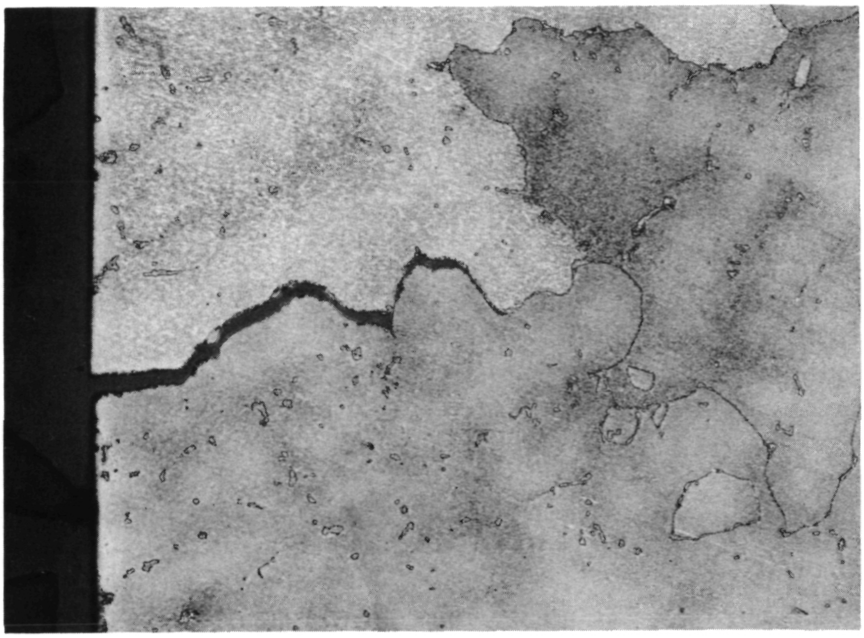


a) 100X Magnification

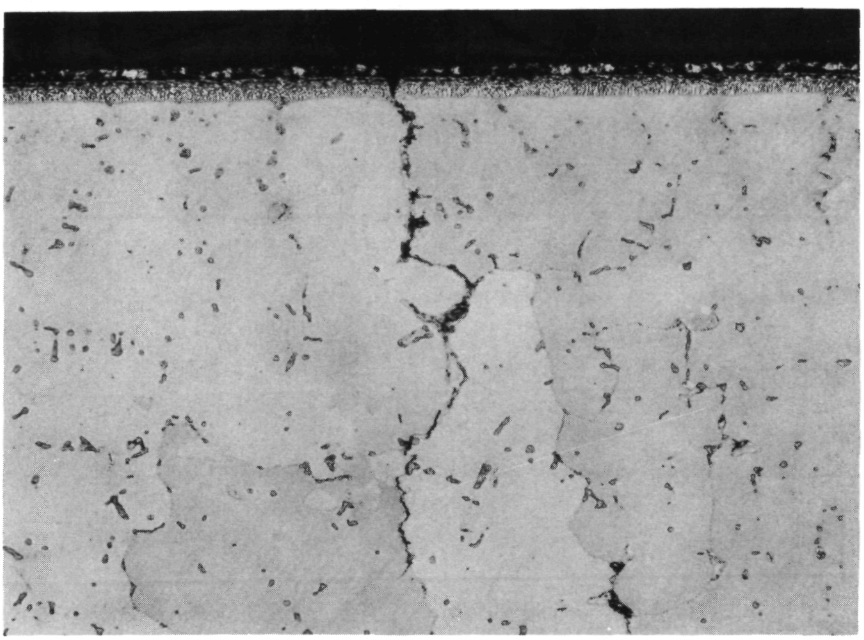


b) 500X Magnification

Figure 16. Light photomicrographs of coated fatigue specimen 57C-PC-2, tested at 1000°C (1832°F), total strainrange of 0.00450. Failure occurred after 386 cycles. Note grain extrusion and intergranular cracking as a result of PC deformation. Fry's etch.

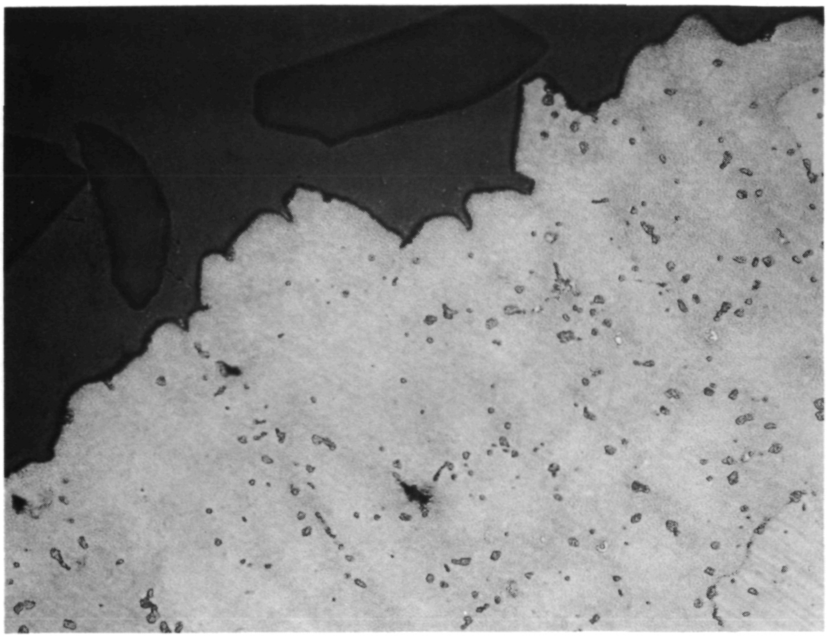


a) Uncoated specimen 31U-CP-6, tested at 871°C (1600°F), total strainrange of 0.00586, 530 cycles to failure.

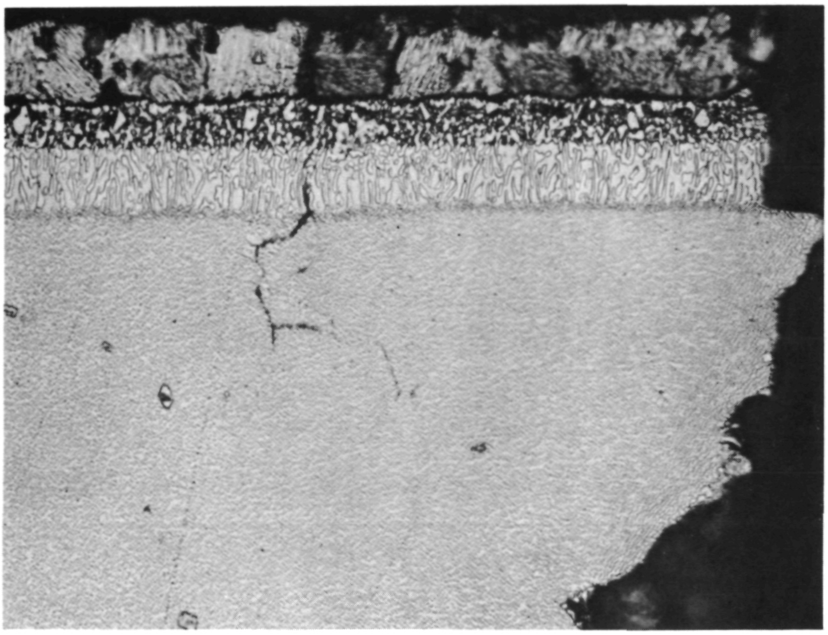


b) Coated specimen 62C-CP-1, tested at 871°C (1600°F), total strainrange of 0.00995, 150 cycles to failure.

Figure 17. Light photomicrographs of intergranular fracture mode in specimens tested with the CP type deformation. Fry's etch. 100X magnification.



a) Intergranular Fracture Mode in Coated Specimen 68C-CC-1, Tested at 1000°C (1832°F), .01135 Total Strainrange, 17 Cycles to Failure 100X



b) Transgranular Fracture Mode in Coated Specimen 69C-CC-2, Tested at 871°C (1600°F), .01005 Total Strainrange, 108 Cycles to Failure. 500X

Figure 18. Light Photomicrographs Showing Examples of Fracture Modes for Specimens Tested with the CC Type Deformation. Fry's etch.

Specimens tested with the PP type deformation exhibited primarily a transgranular fracture mode for all test temperatures and surface conditions. This is a common fracture mode for materials tested at high frequencies where creep deformation is negligible. This fracture mode reflects the fact that the PP deformation resulted in the highest fatigue lives. Transgranular crack propagation in a highly alloyed cast nickel-base superalloy such as Rene' 80 is retarded by the heavy matrix precipitation of the gamma-prime strengthening phase. For uncoated specimens, grain boundary areas at the specimen surface were common crack initiation sites, with the cracks becoming transgranular after a short distance, Figure 13a. Crack initiation was also observed at grain boundary microporosity, Figure 13b. After initiation in the grain boundary region these cracks become transgranular. For coated specimens, considerable numbers of coating cracks were observed leading to transgranular crack propagation, Figure 14. Since the fatigue results for the PP type tests, Figure 7, indicated no appreciable differences in failure times as a function of surface condition, the presence of the aluminide coating and its attendant cracks did not degrade the low cycle fatigue properties of this alloy.

Specimens tested with the PC type deformation exhibited a predominantly intergranular fracture mode. In general, intergranular crack initiation and propagation occur at a faster rate than transgranular cracking in nickel-base superalloys and the presence of this fracture mode in PC specimens suggests why this type of strain cycling resulted in lower fatigue lives than the PP type. At 1000°C (1832°F) there was considerable evidence of grain boundary sliding which took place during the compressive (creep) portion of the cycle resulting in steps or grain extrusions along the sides of the specimens. Examples of these extrusions are shown in Figure 15 for the uncoated material and Figure 16 for coated material. Specimens tested at 871°C (1600°F) did not exhibit the extent of grain boundary sliding seen at 1000°C (1832°F). Considerable numbers of surface cracks were observed in the coated specimens, but, similar to the PP specimens, the presence of the aluminide coating and its attendant cracks did not degrade the low cycle fatigue properties of this alloy.

Specimens tested with the CP type deformation exhibited primarily an intergranular type of fracture mode both at 1000°C (1832°F) and 871°C (1600°F), Figure 17. Unlike materials such as iron base A-286 and 304 stainless alloys which exhibit intergranular fracture resulting from internal grain boundary "decohesion" as a consequence of CP cycling (4), specimens of Rene' 80 studied in the present investigation usually exhibited some form of surface grain boundary cracking into the specimen. High magnification SEM analyses of Rene' 80 specimens revealed no internal grain boundary "decohesion" or cavitation in this alloy. In addition, the CP specimens did not exhibit the grain boundary sliding observed in the PC specimens and this may explain why the CP failure lives were slightly higher. Similar to the results for the PP testing, the presence of numerous coating cracks did not result in an appreciable degradation in fatigue results, Figure 9.

Specimens tested with the CC type deformation exhibited different fracture modes depending on the test temperature. At 1000°C (1832°F) the fracture mode was primarily intergranular, while at 871°C (1600°F) the fracture mode was transgranular. Examples of these various modes are shown in Figure 18. There was no evidence of grain boundary extrusion at the specimen surface or of internal grain boundary decohesion or cavitation in these specimens.

C. Supplementary Mechanical Property Tests

The results of the supplemental vacuum tensile and creep rupture tests are presented in Appendix B in Tables B-1 and B-2.

VI SUMMARY

The results of ultrahigh vacuum low cycle fatigue tests conducted on uncoated and CODEP B-1 aluminide coated specimens of Rene' 80 nickel-base superalloy at 1000°C (1832°F) and 871°C (1600°F) indicated little effect of coating or temperature on the fatigue properties. There was, however, a significant effect on fatigue life as a function of strain cycle type. The method of Strainrange Partitioning offers an appropriate framework around which to correlate the effects of these strain cycle types. In terms of partitioned inelastic strainrange, the completely reversed plasticity type of strain cycling (PP) resulted in the highest fatigue lives. When a time-dependent creep component was introduced into the cycle, an effect was observed which was dependent upon which portion of the cycle contained the creep component. When creep was introduced in the compressive portion of the cycle (PC) failure lives were approximately one order of magnitude below those for PP deformation. When creep was introduced in the tensile portion of the cycle (CP), failure lives were slightly higher than those for the PC deformation, i.e., slightly less than an order of magnitude below those for PP. The least damaging of the creep type cycling was CC in which creep occurred both in the tensile and compressive portions of the cycle resulting in failure lives approximately 1/2 an order of magnitude below those for PP.

Metallographic evaluation indicated that microstructural damage varied with cycle type and test temperature. Specimens tested with the PP type deformation exhibited primarily a transgranular fracture mode. Specimens tested with the PC type deformation exhibited a predominantly intergranular fracture mode. At 1000°C (1832°F) there was considerable evidence of grain boundary sliding which took place during the compressive (creep) portion of the cycle resulting in steps or grain extrusions along the sides of the specimens. Specimens tested at 871°C (1600°F) did not evidence the same extent of grain boundary extrusion. Specimens tested with the CP type deformation exhibited an intergranular type of fracture mode at both test temperatures. Specimens tested with the CC type deformation exhibited different fracture modes depending on the test temperature. At 1000°C (1832°F) the fracture mode was intergranular while at 871°C (1600°F) the fracture mode was transgranular. At both test temperatures considerable evidence of surface cracking was observed in coated specimens for all the types of strain cycling.

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APPENDIX A

HYSTERISIS LOOPS

TABLE A-1

MODULUS OF ELASTICITY USED TO CALCULATE ELASTIC STRAIN IN LOW CYCLE FATIGUE TESTS CONDUCTED IN THIS PROGRAM(1)

Test Temperature °F	Test Temperature °C	Modulus of Elasticity 10^6
Room	Room	29.98
400	204	28.78
1000	538	26.26
1200	649	25.29
1400	760	24.15
1600	871	22.76
1832	1000	20.90

(1) Modulus of elasticity data obtained from General Electric Co. Aircraft Engine Group, Materials Data Unit, Cincinnati, Ohio 45215, 10-8-74.

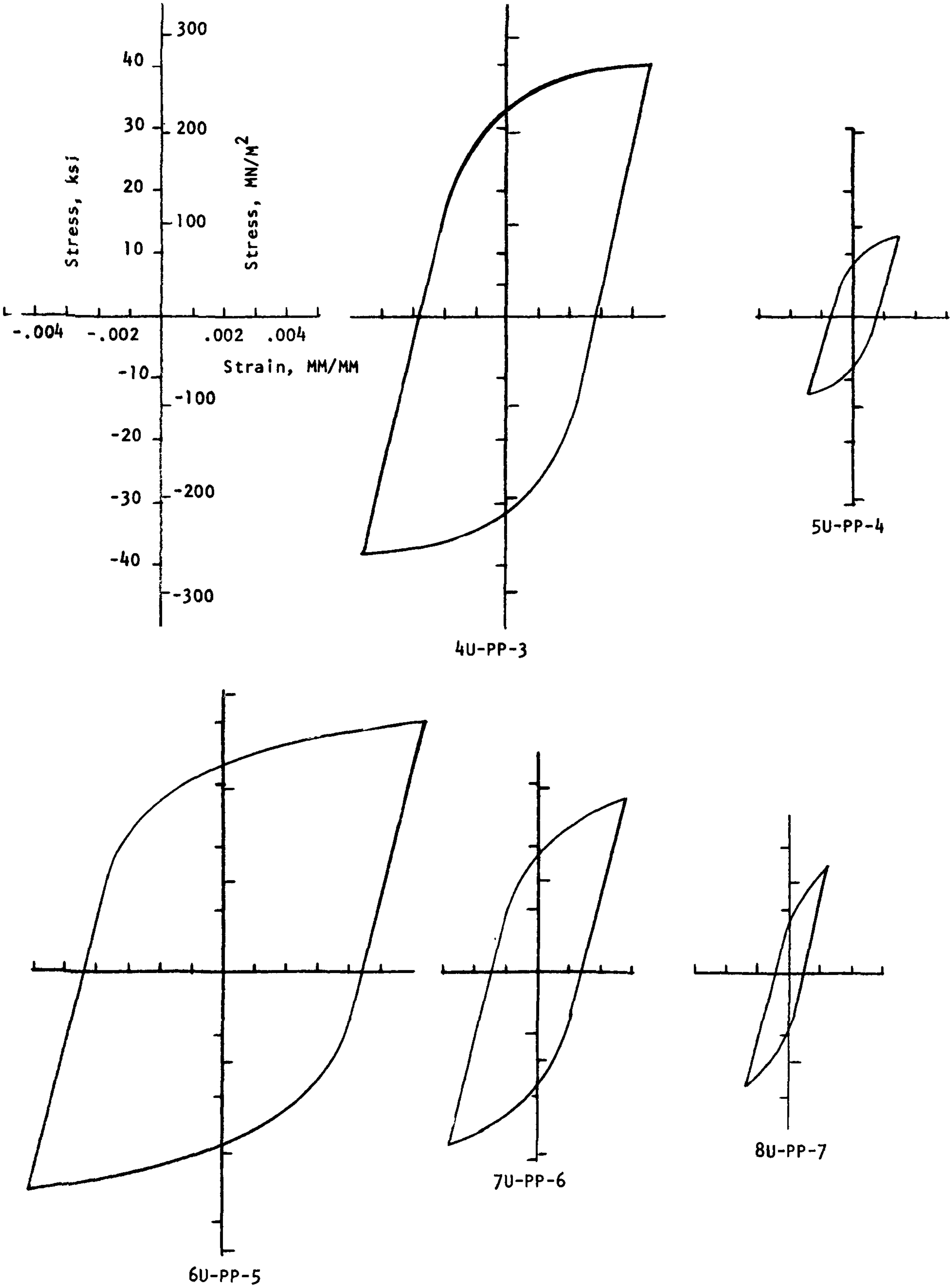

Figure A-1. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 1000°C (1832°F) with the $\Delta\varepsilon_{pp}$ Deformation.

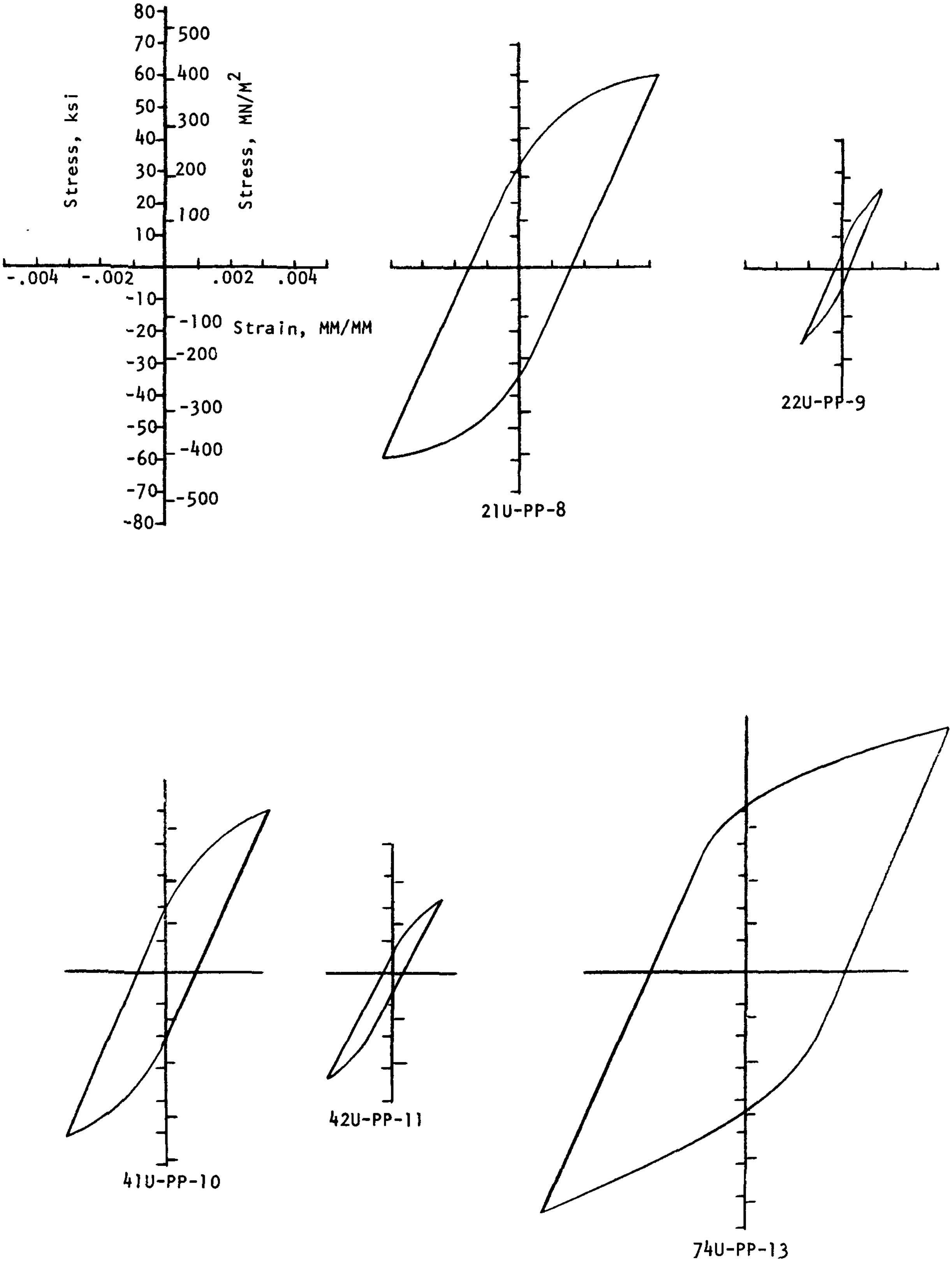

Figure A-2. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 871°C (1600°F) with the $\Delta\varepsilon_{pp}$ Deformation.

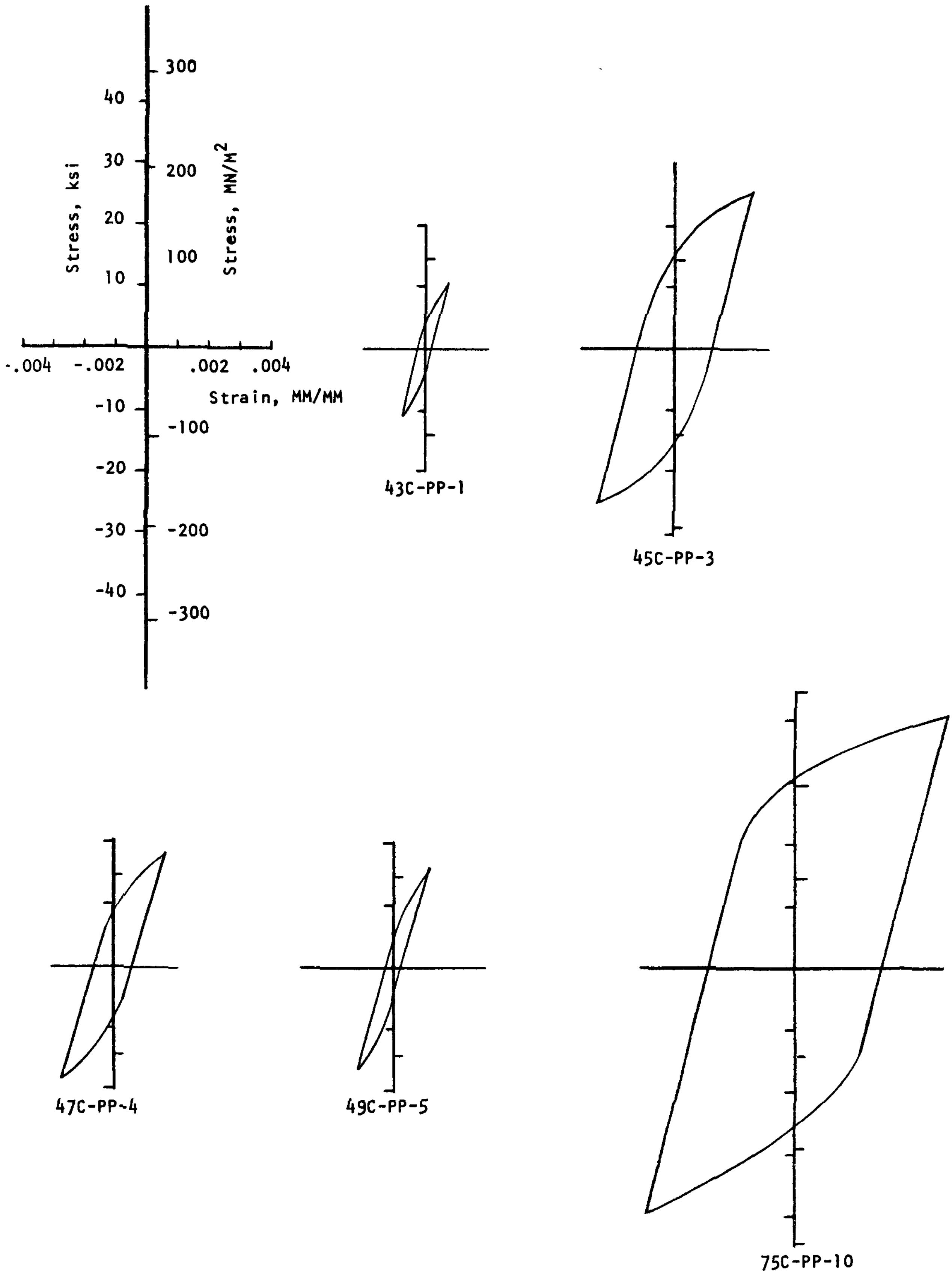

Figure A-3. Hysterisis Loops Observed for Coated Rene' 80 Tested at 1000°C (1832°F) with the $\Delta\varepsilon_{pp}$ Type Deformation.

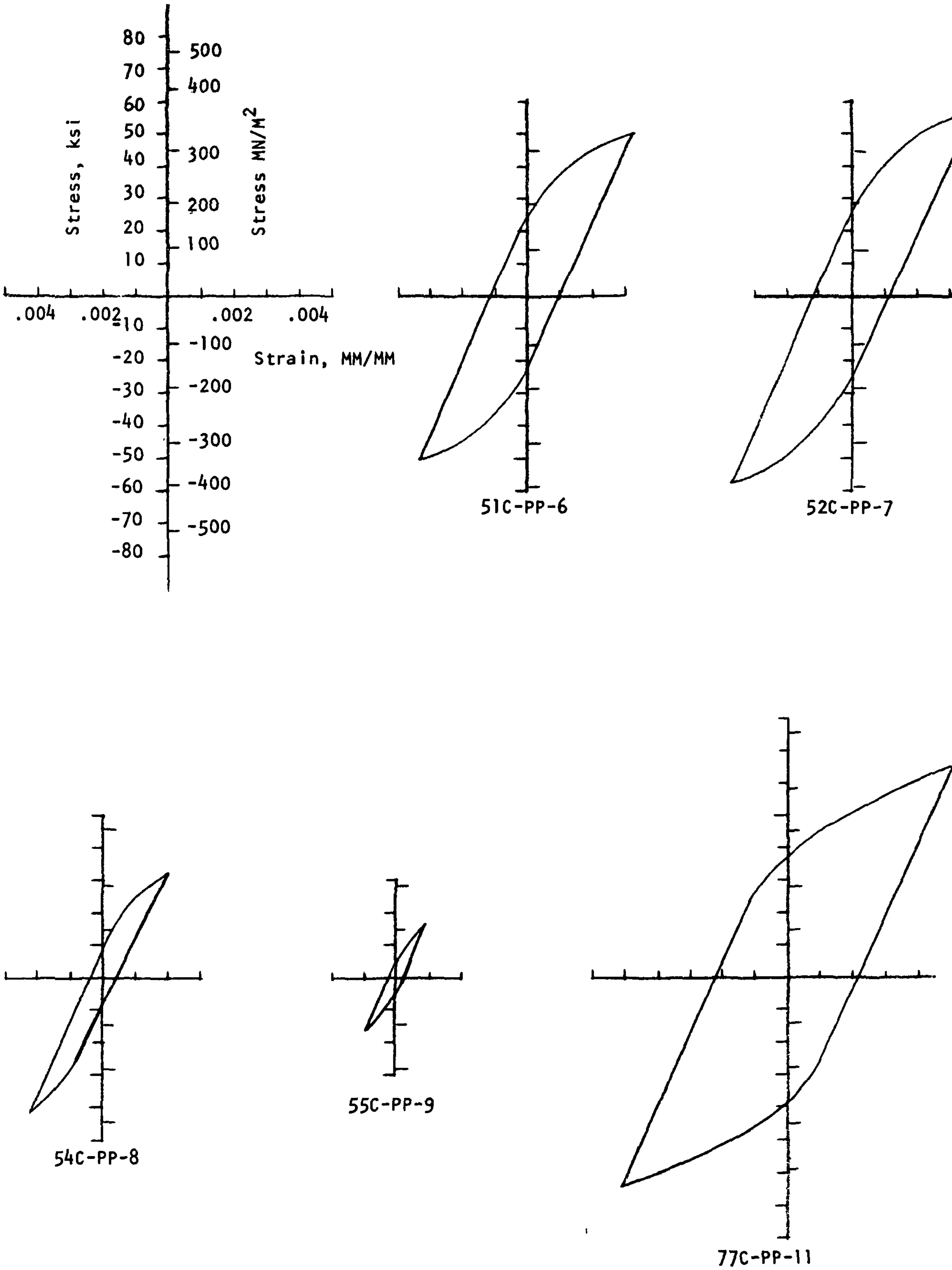

Figure A-4. Hysterisis Loops Observed for Coated Rene' 80 Tested at 871°C (1600°F) with the $\Delta\epsilon_{pp}$ Type Deformation.

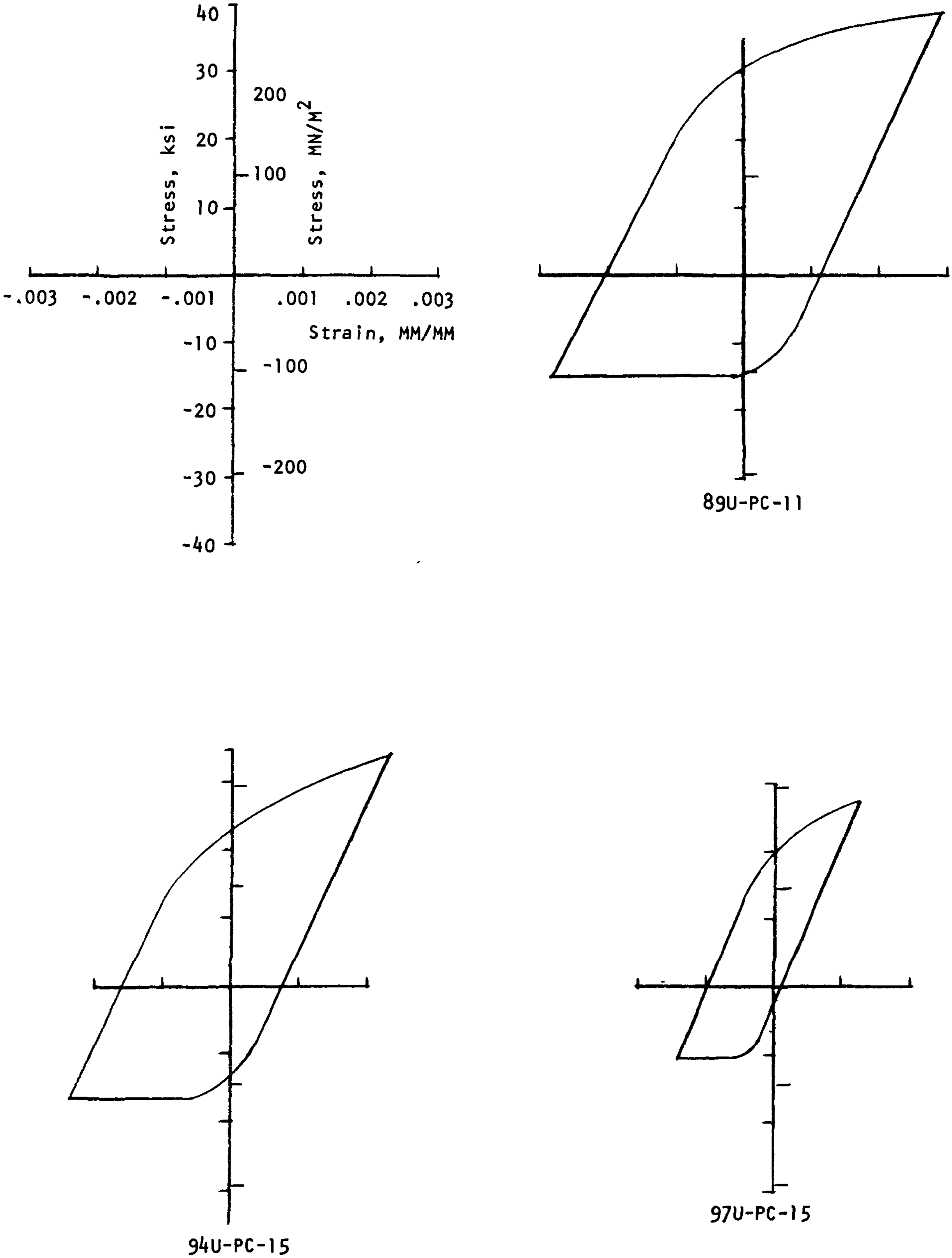

Figure A-5. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 1000°C (1832°F) with the $\Delta\varepsilon_{pc}$ Type Deformation.

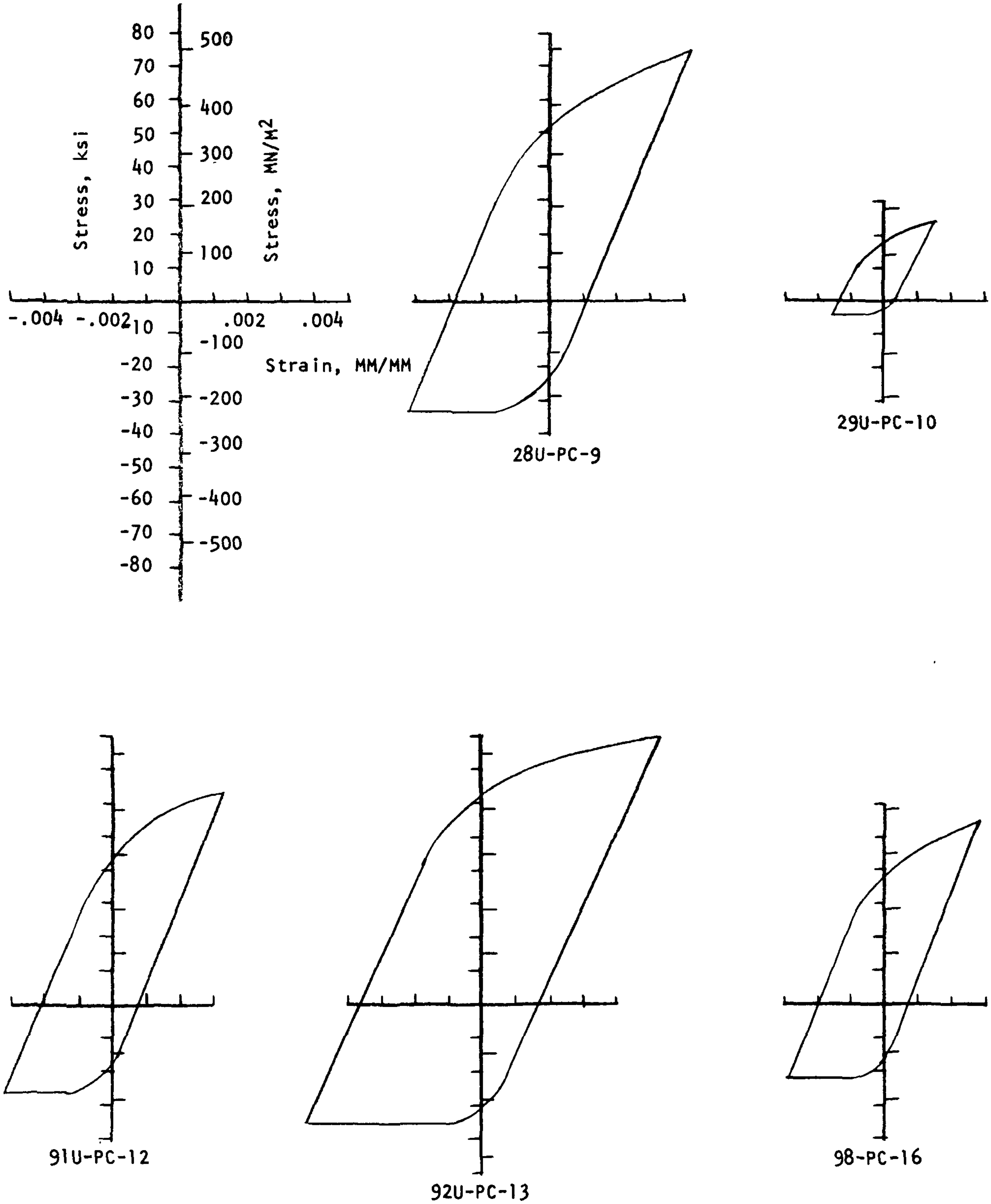

Figure A-6. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 871°C (1600°F) with the $\Delta\varepsilon_{pc}$ Type Deformation.

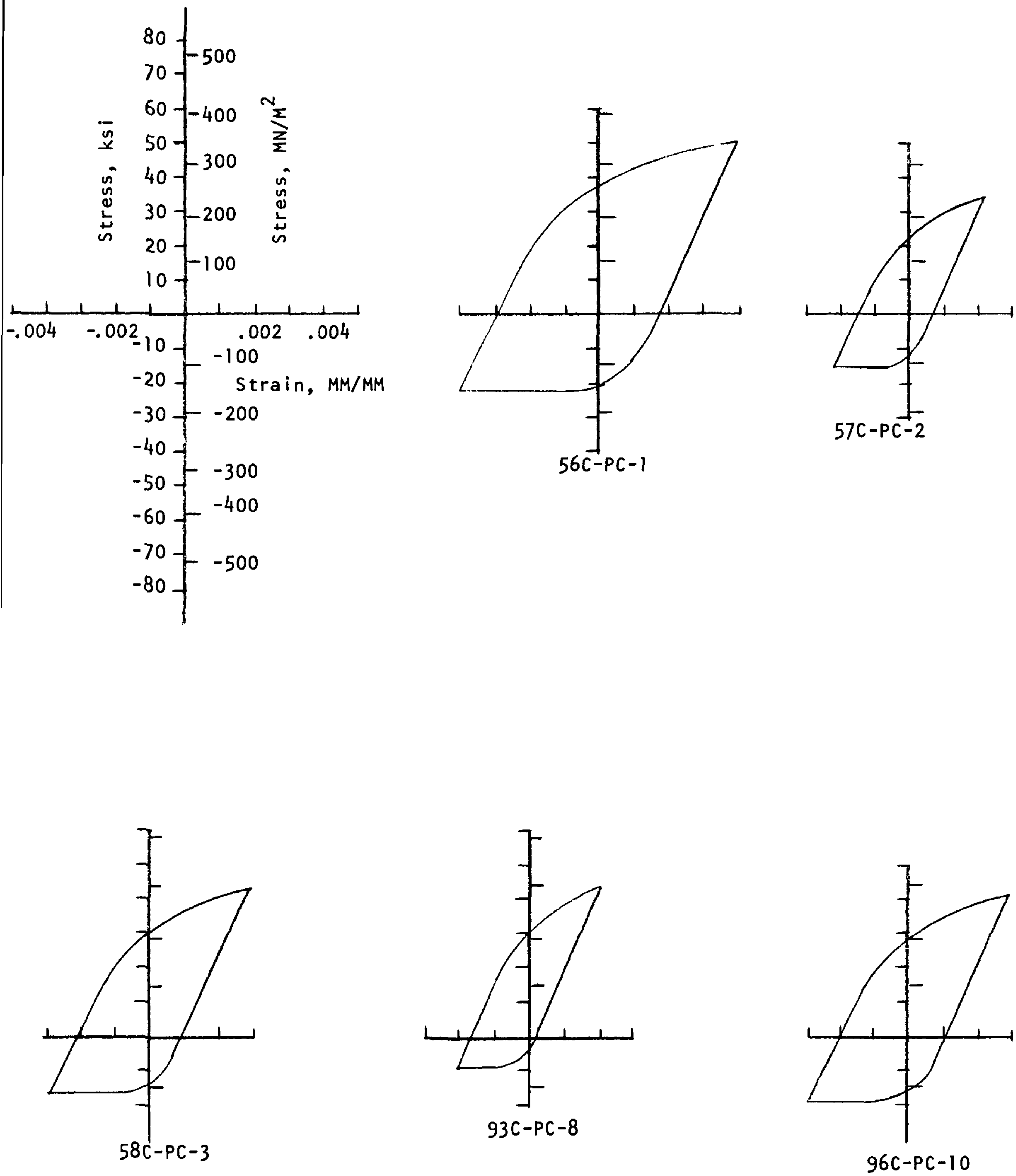

Figure A-7. Hysterisis Loops Observed for Coated Rene' 80 Tested at 1000°C (1832°F) With the $\Delta\varepsilon_{pc}$ Type Deformation.

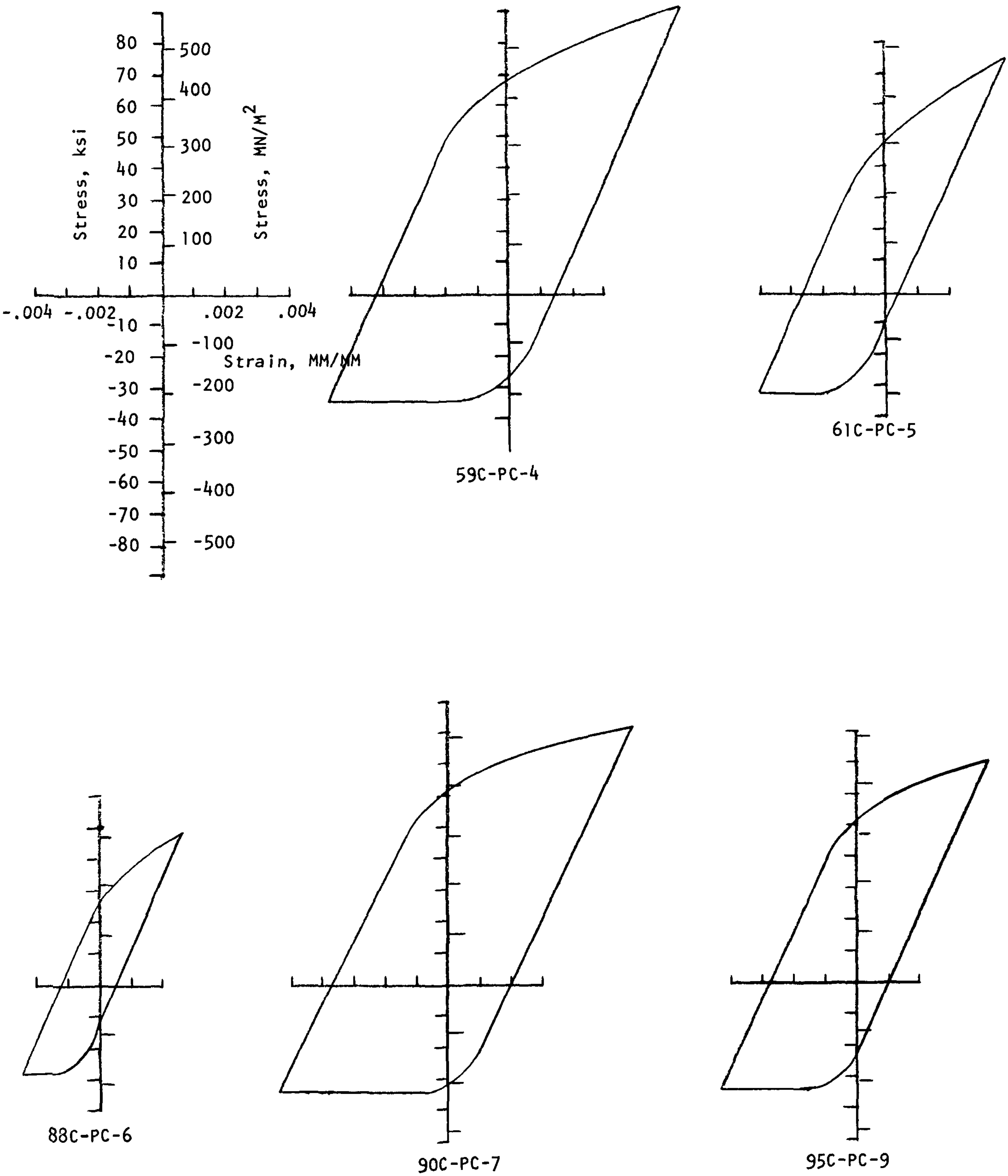

Figure A-8. Hysterisis Loops Observed for Coated Rene' 80 Tested at 871°C (1600°F) With the $\Delta\varepsilon_{pc}$ Type Deformation.

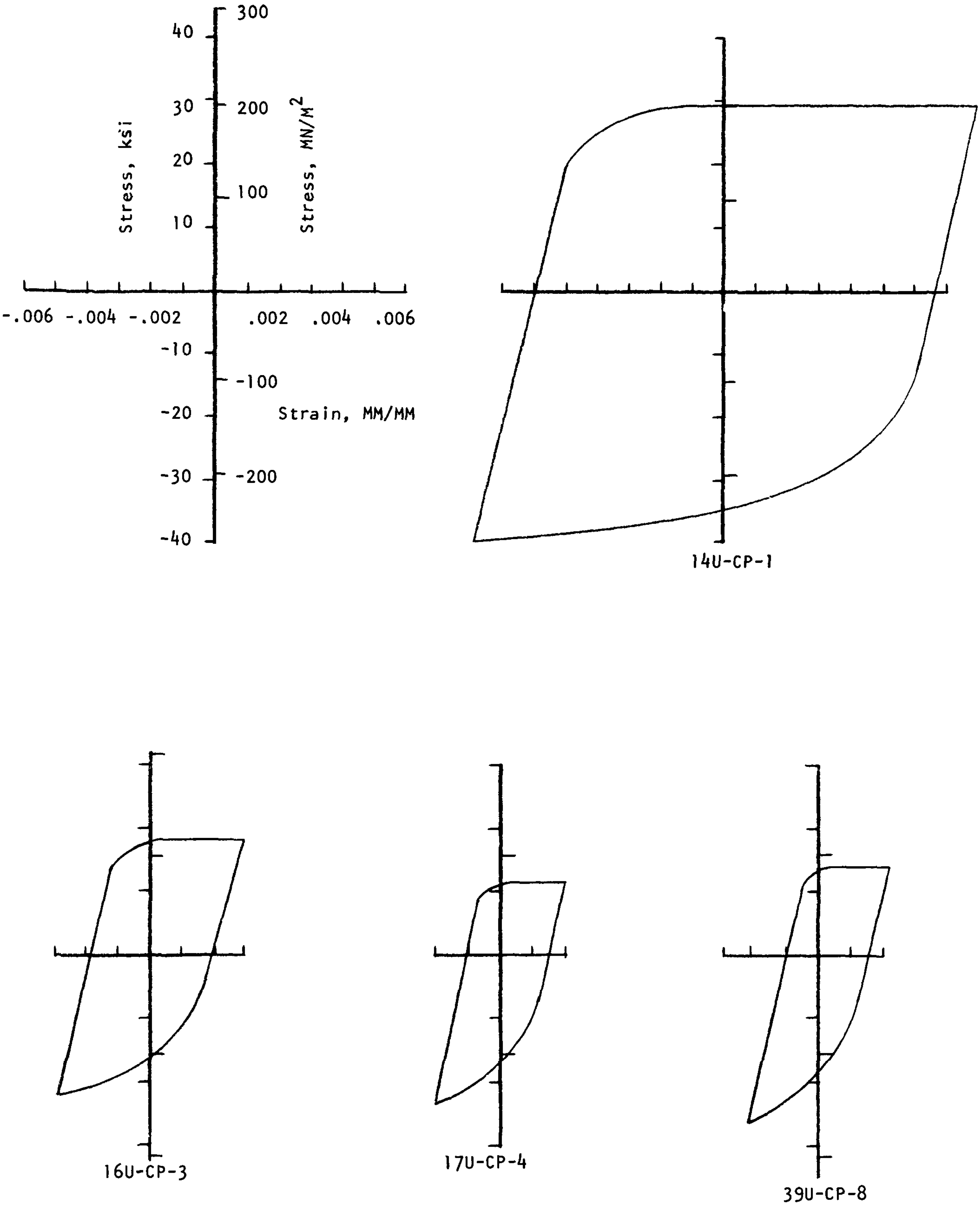

Figure A-9. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 1000°C (1832°F) with the $\Delta\varepsilon_{cp}$ Type Deformation.

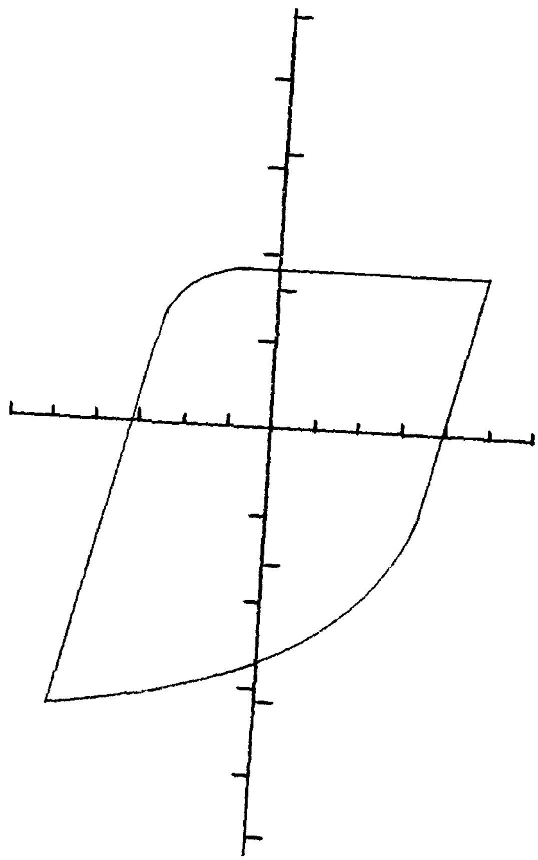

Figure A-9 continued.

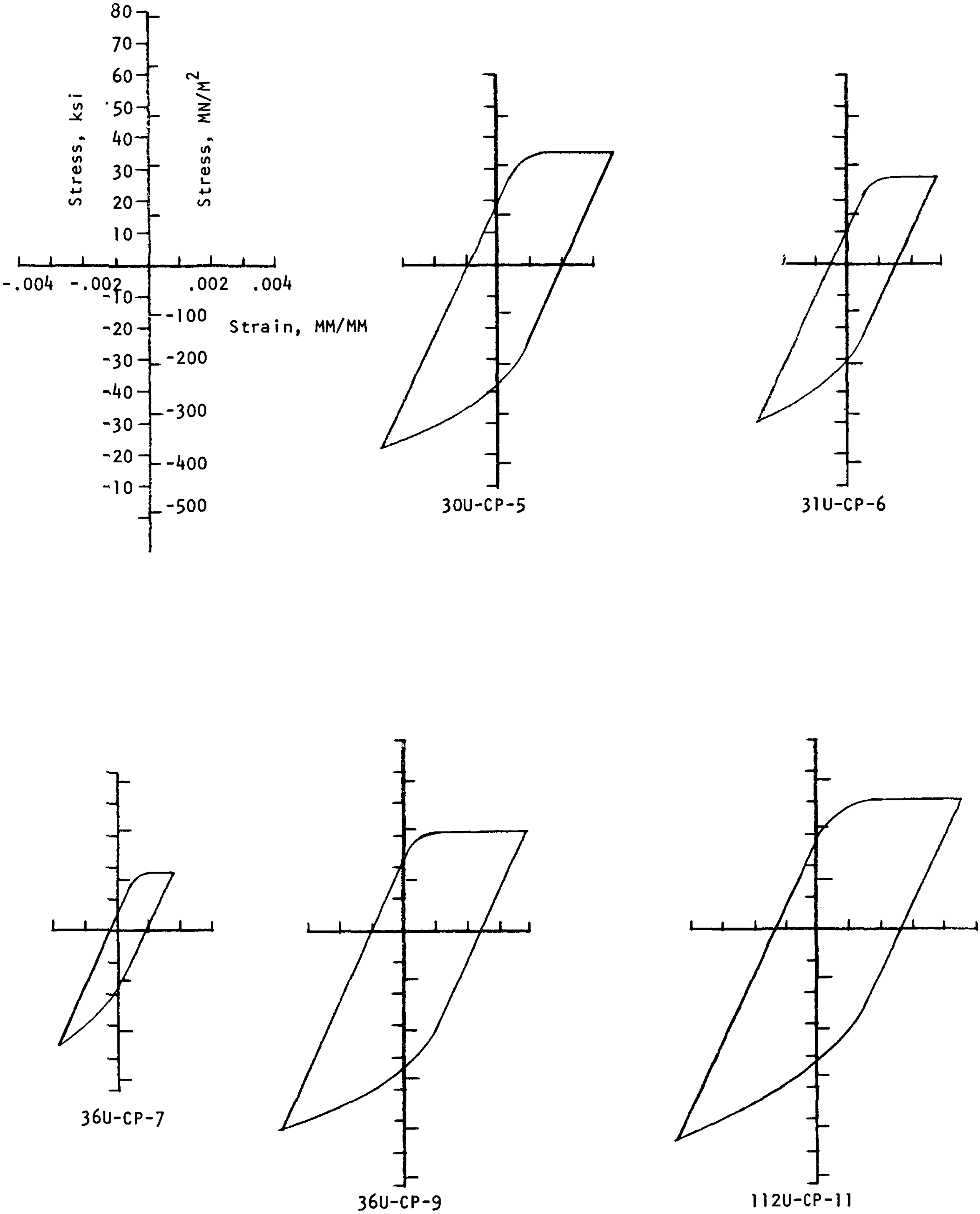

Figure A-10. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 871°C (1600°F) With the $\Delta\varepsilon_{cp}$ Type Deformation.

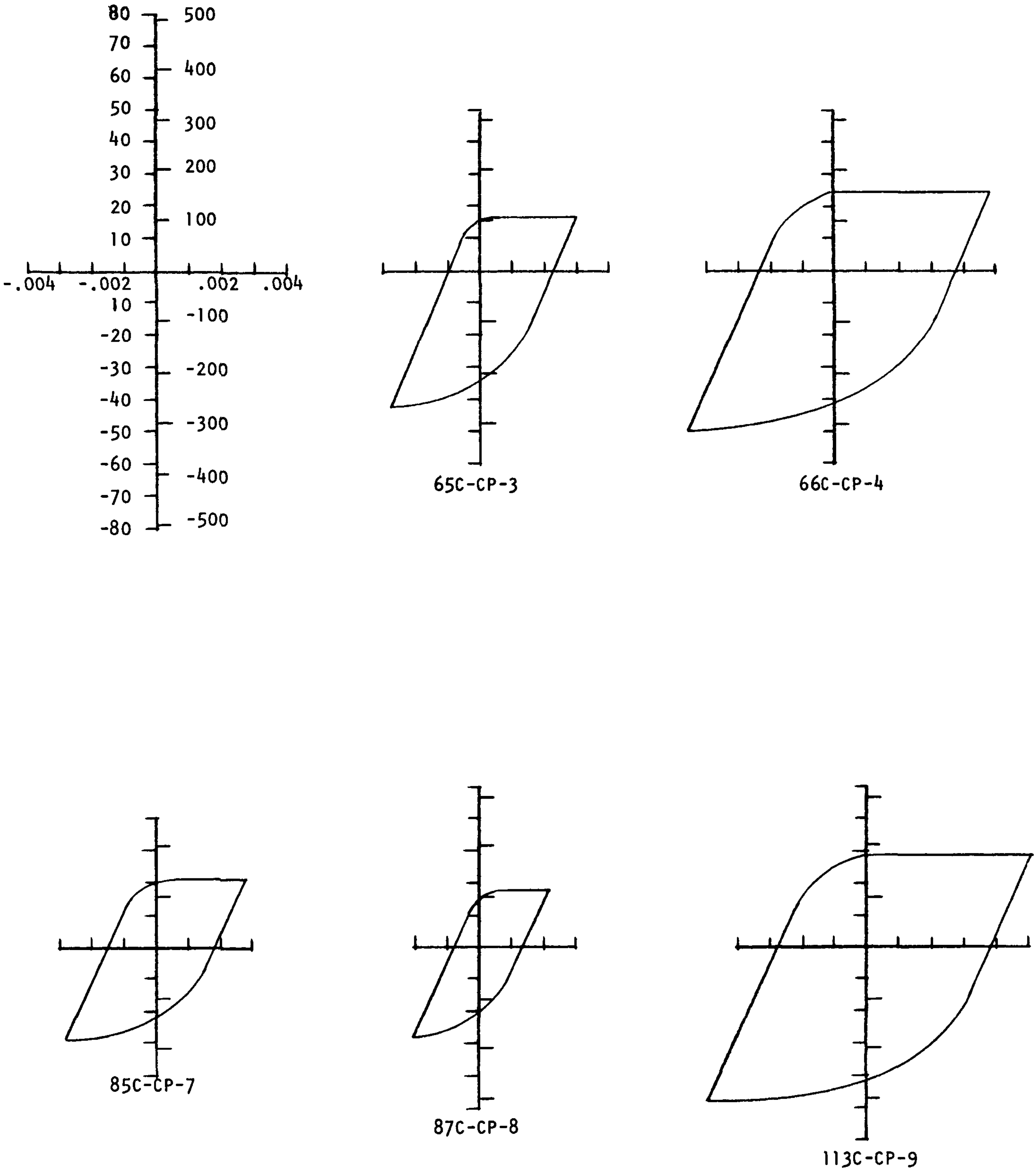

Figure A-11. Hysterisis Loops Observed for Coated Rene' 80 Tested at 1000°C (1832°F) With the $\Delta\varepsilon_{cp}$ Type Deformation.

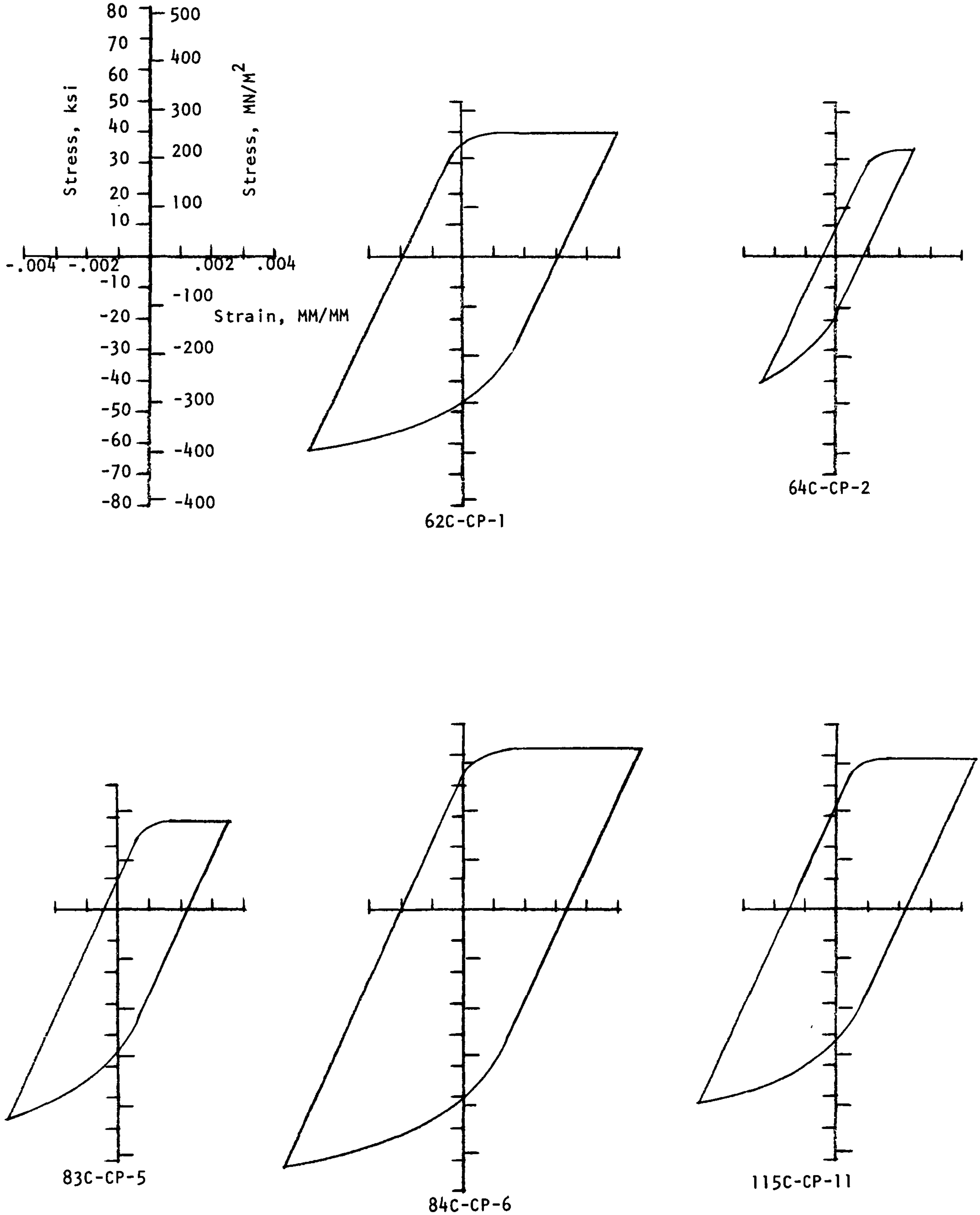

Figure A-12. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 871°C (1600°F) With the $\Delta\varepsilon_{cp}$ Type Deformation.

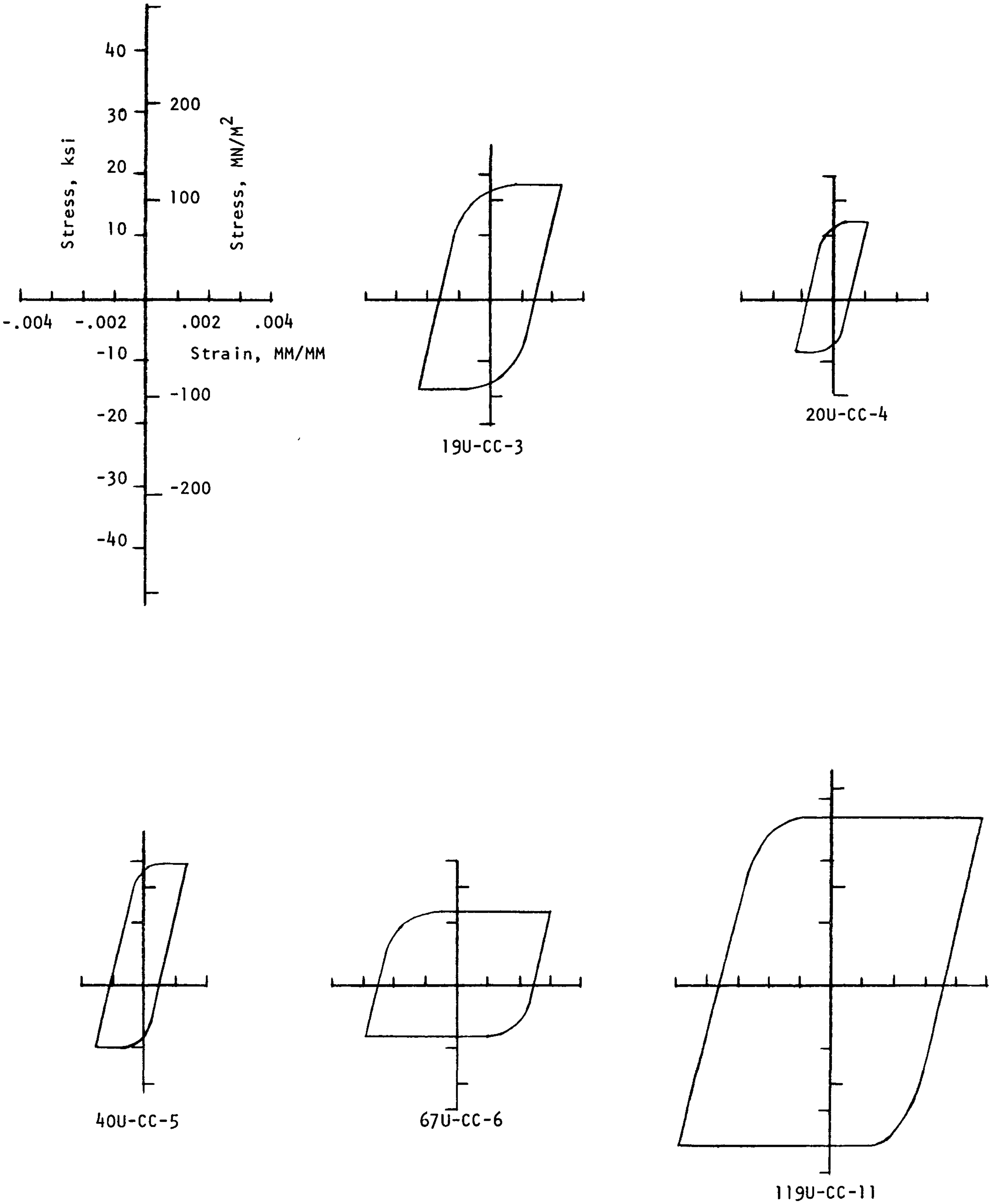

Figure A-13. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 1000°C (1832PF) With the $\Delta\varepsilon_{cc}$ Type Deformation.

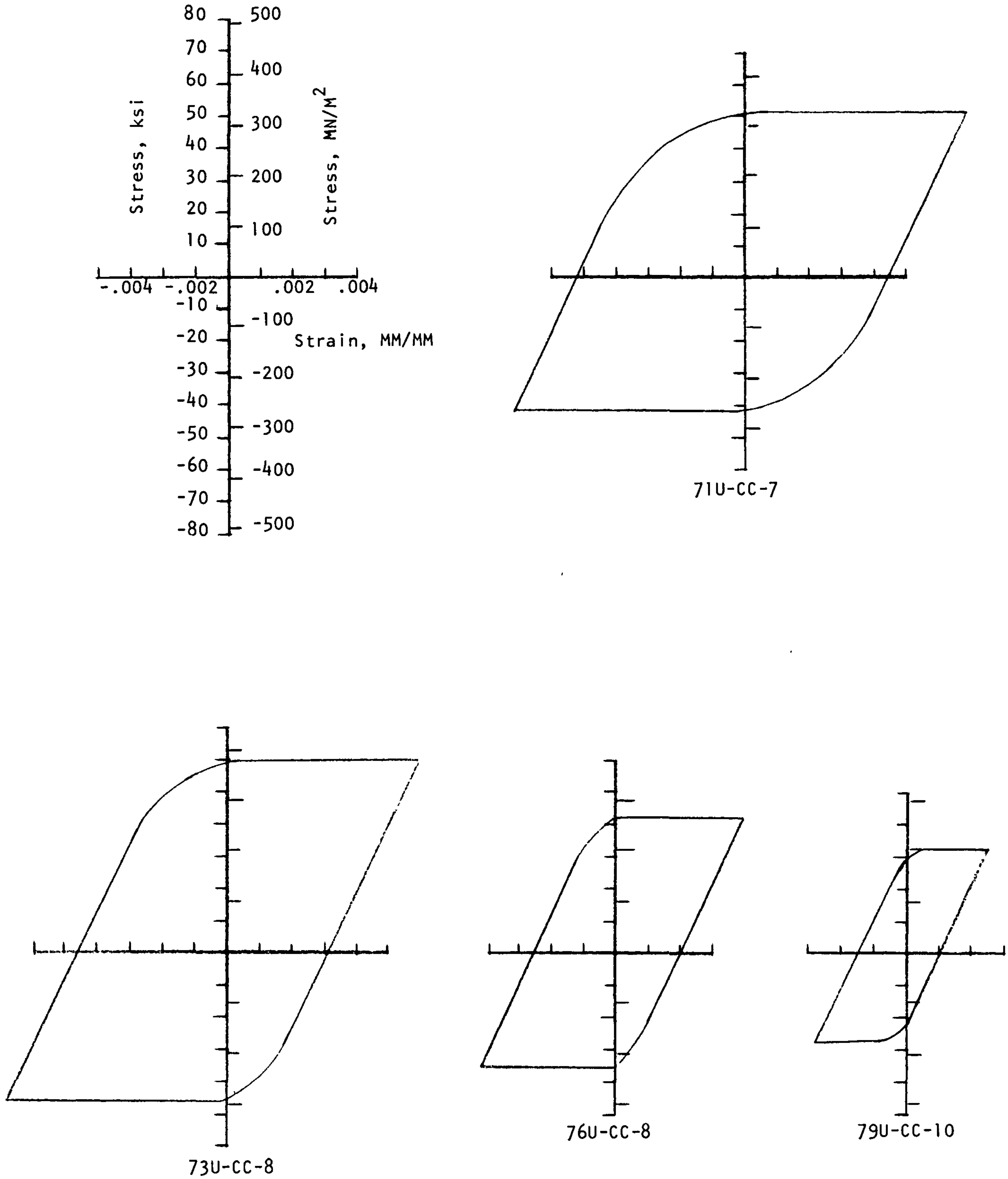

Figure A-14. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at 871°C (1600°F) With the $\Delta\varepsilon_{cc}$ Type Deformation.

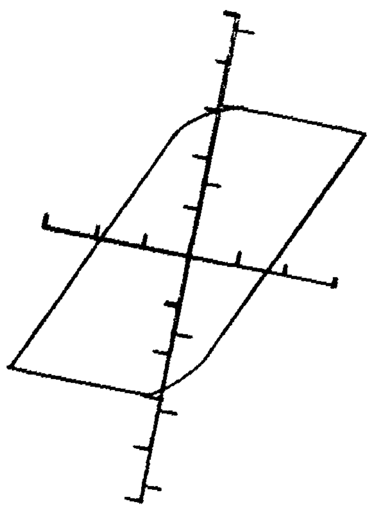

Figure A-14 (continued).

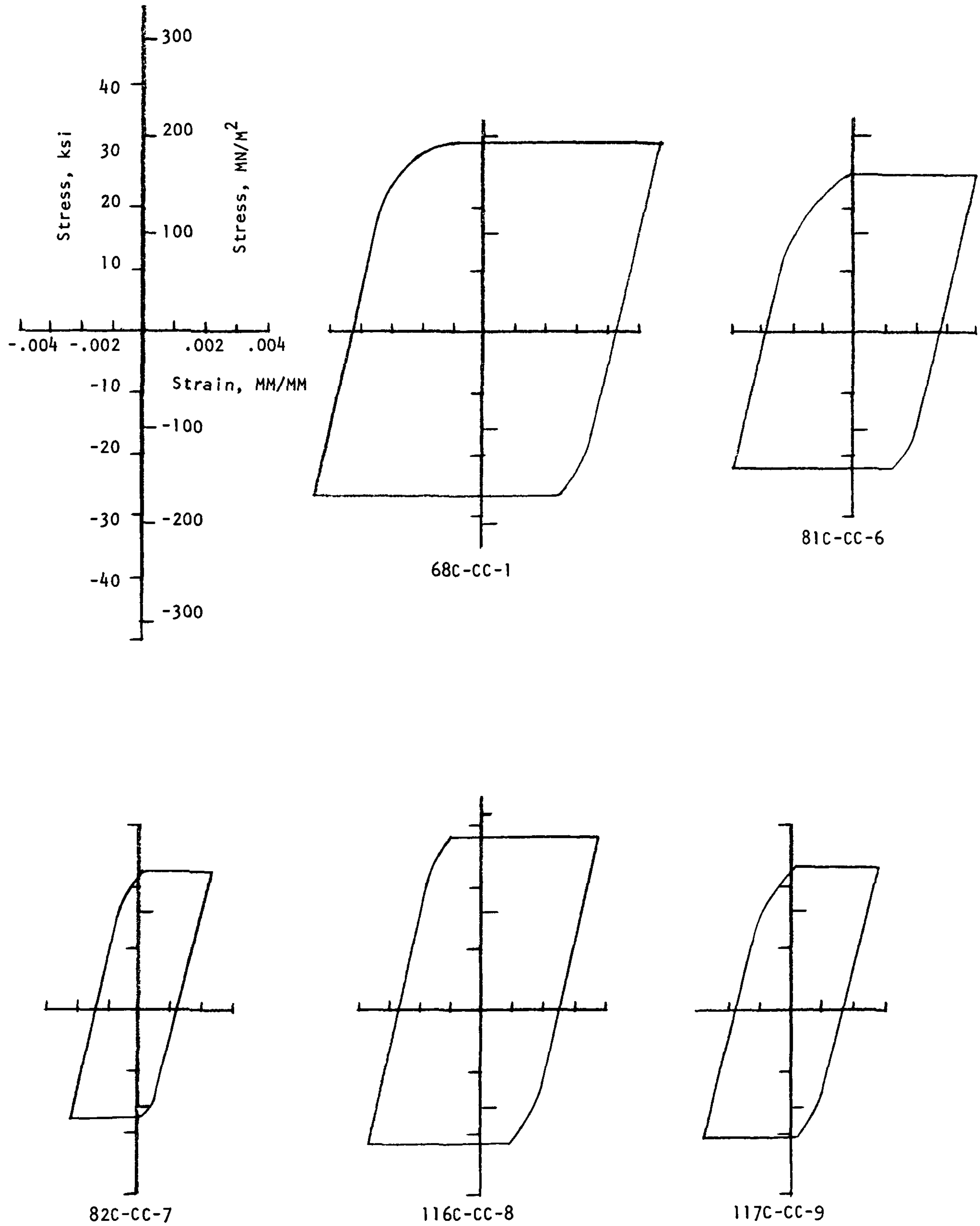

Figure A-15. Hysterisis Loops Observed for Coated Rene' 80 Tested at 1000°C (1832°F) With the $\Delta\varepsilon_{cc}$ Type Deformation.

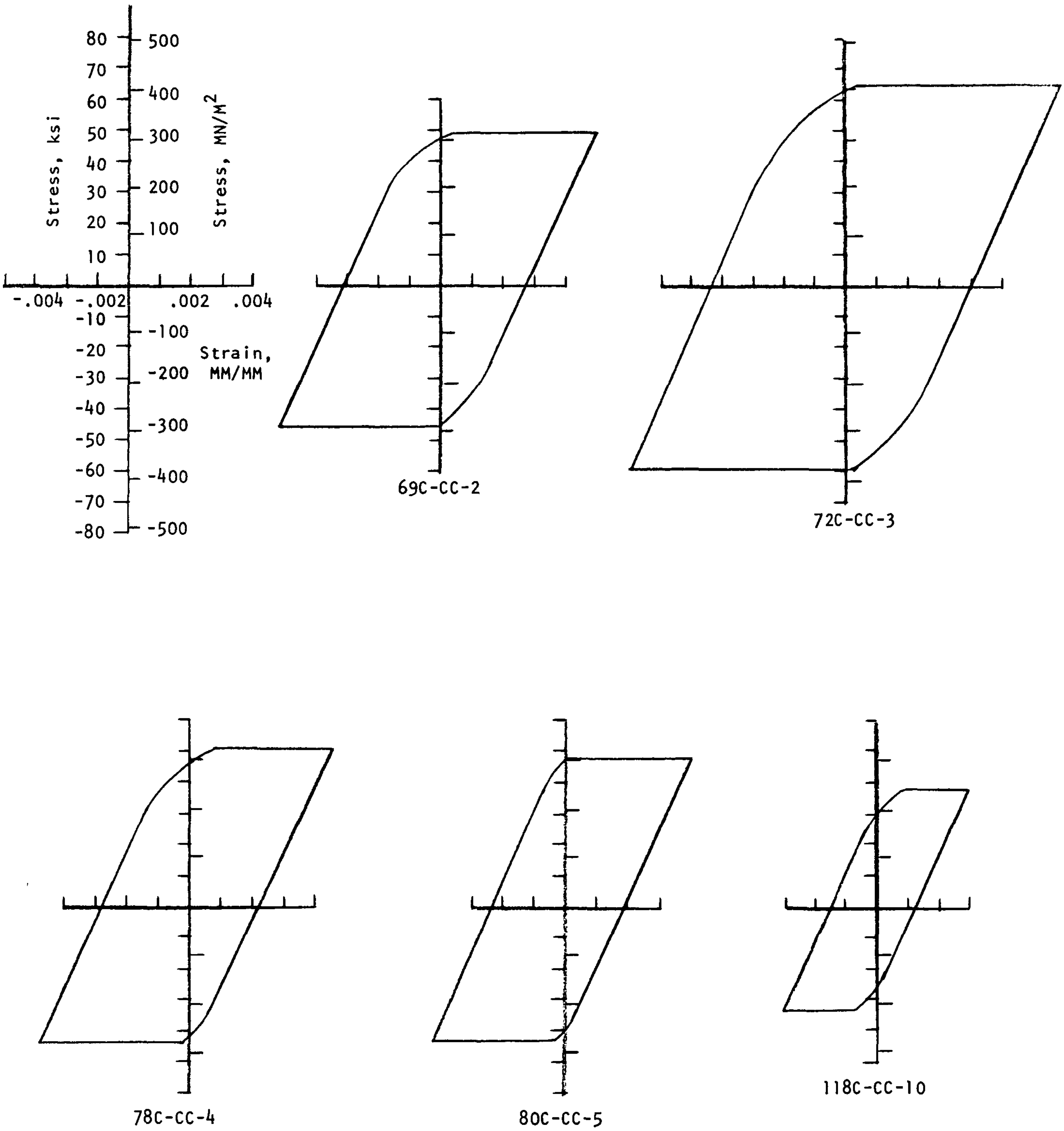

Figure A-16. Hysterisis Loops Observed for Coated Rene' 80 Tested at 871°C (1600°F) With the $\Delta\varepsilon_{cc}$ Type Deformation.

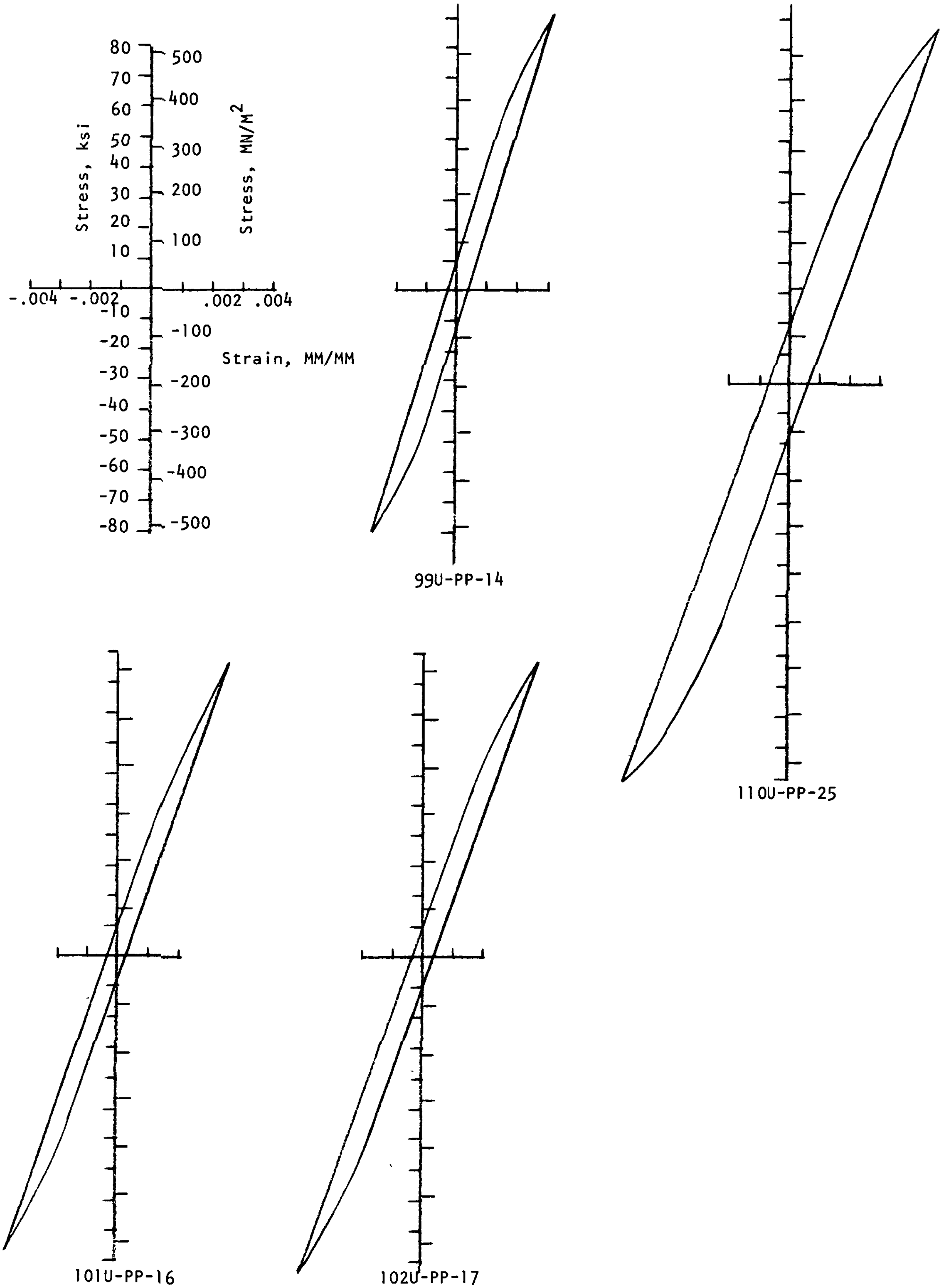

Figure A-17. Hysterisis Loops Observed for Uncoated Rene' 80 Tested at Various Temperatures with the $\Delta\varepsilon_{pp}$ Type Deformation.

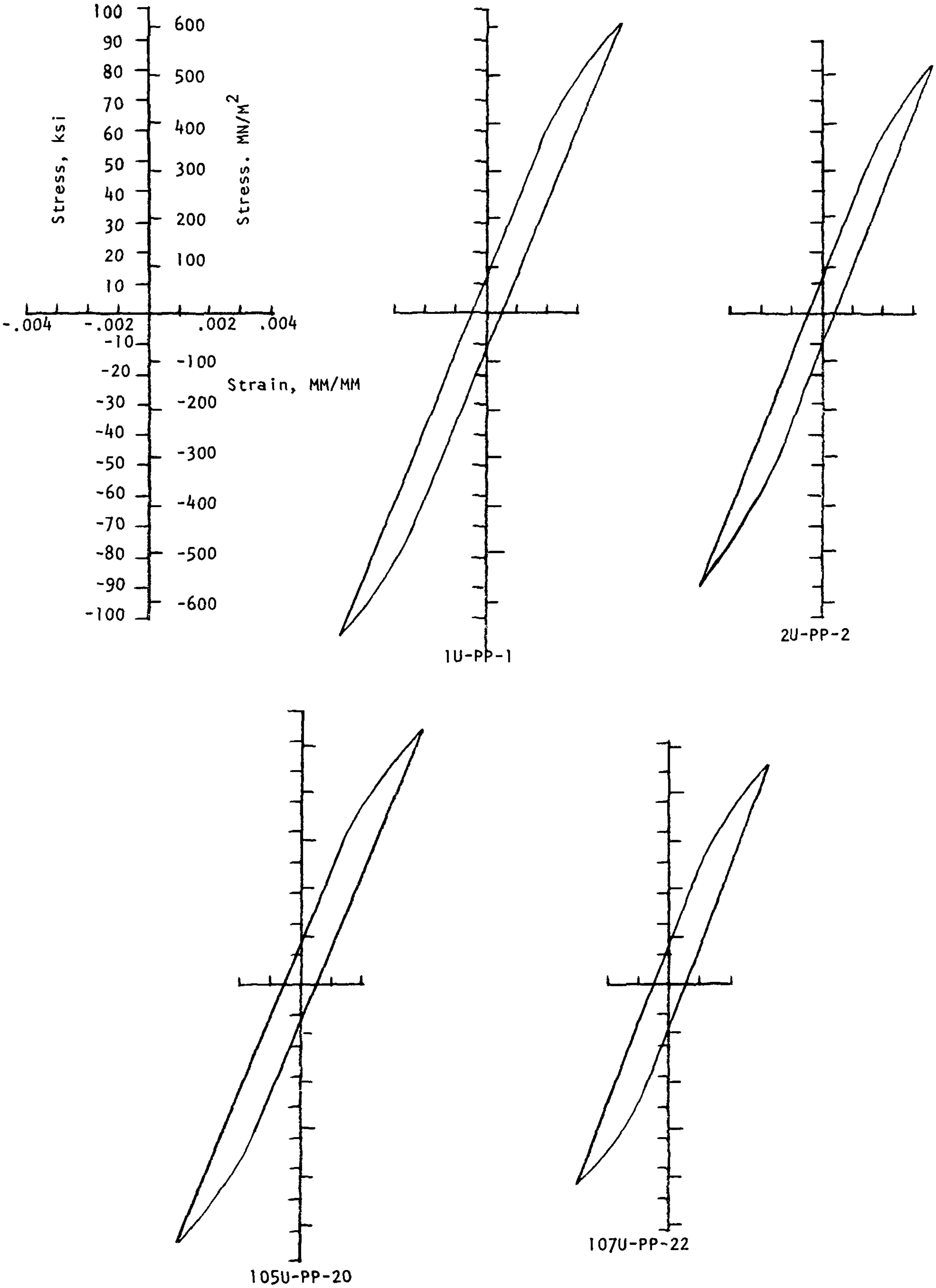

Figure A-17 (continued).

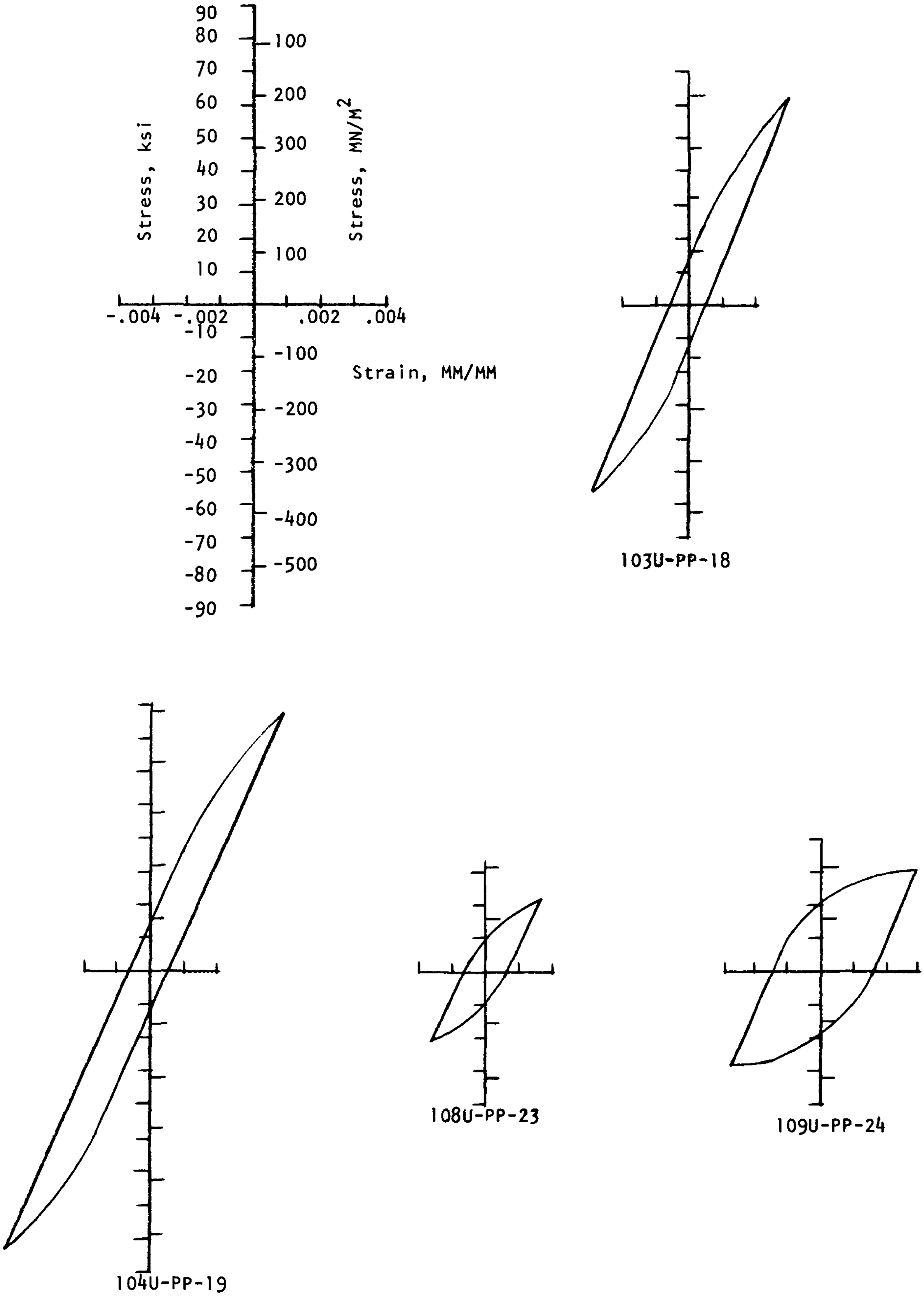

Figure A-17 (continued)

APPENDIX B

TABLE B-1

RENE' 80 TENSILE RESULTS

Specimen Number(1)	Temperature °F	Temperature °C	Ultimate Tensile Strength ksi	Ultimate Tensile Strength MN/M²	0.2% Yield Strength ksi	0.2% Yield Strength MN/M²	Percent Reduction Area %
123C-T-3	1600	871	110.4	761.2	83.4	575.1	27.8
124C-T-4	"	"	114.0	786.0	80.1	552.3	20.8
125U-T-1	"	"	106.8	736.3	79.3	546.8	27.5
126U-T-2	"	"	111.4	768.1	76.8	529.5	30.1
121C-T-1	1832	1000	67.5	465.4	33.4	230.3	29.7
122C-T-2	"	"	70.1	483.3	34.0	234.4	31.2
127U-T-3	"	"	62.2	428.9	34.2	235.8	33.5
128U-T-4	"	"	61.4	423.4	33.3	229.6	32.8

RENE' 80 CREEP RESULTS

Specimen Number(1)	Temperature °F	Temperature °C	Stress Level ksi	Stress Level MN/M²	Rupture Life hours	Percent Reduction Area
37U-C-7	1600	871	50.0	344.7	2.1	31.0
38U-C-8	"	"	35.0	241.3	84.8	23.0
53C-C-4	"	"	50.0	344.7	9.4	28.3
60C-C-5	"	"	45.0	310.3	66.6	20.6
25U-C-1	1832	1000	30.0	206.8	0.7	29.7
35U-C-6	"	"	25.0	172.4	1.0	31.1
33U-C-4	"	"	15.0	103.4	48.7	29.5
32U-C-3	"	"	15.0	103.4	52.6	32.1
63C-C-6	"	"	23.0	158.6	15.4	29.6
46C-C-1	"	"	15.0	103.4	60.0	31.1
48C-C-2	"	"	15.0	103.4	21.6	35.1

(1) The first letter in the specimen number designation stands for coated (C) or uncoated (U) material, while the second letter stands for a tensile (T) or creep (T) type of test.

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